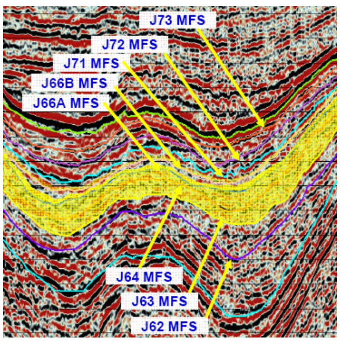
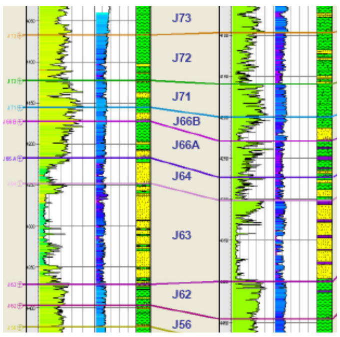
Master Thesis in Geosciences

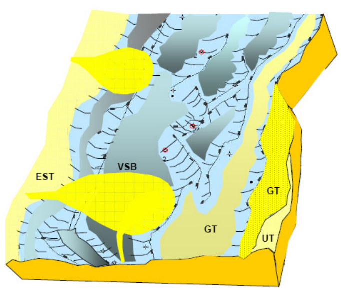
Provenance and Depositional Environment of Deeply Buried Upper Jurassic Sandstones of the South Viking Graben

by

Tanjina Islam







UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Discipline: Petroleum Geology and Geophysics

Department of Geosciences

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Abstract

Late Jurassic transgressions in the North Sea area developed thirteen genetic stratigraphic sequences containing sand bodies with in the shale dominated Heather and Draupne formations in the South Viking Graben area. Thirteen genetic stratigraphic sequences with three facies associations have been mapped regionally in an area ranging from 58º45″–59º15″ N .The main challenge in this study is to establish the depositional model of the Upper Jurassic sandstones of the South Viking Graben.

This study includes both 3D and 2D seismic surveys for seismic interpretation, well cores, well logs and biostratigraphic information for facies identifications of the late Jurassic sequences. Identified sand bodies in the study area show variation in marine to deep marine deposits and extremely variable thickness because sediment depositional systems reflect a complex relationship between a range controls including sea level fluctuations, basin tectonics, the rate, type and nature of sediment supply.

The depositional model shows the spatial distribution of the Upper Jurassic sand bodies and the facies distribution from well to well. The vertical thickness facies maps of the sand bodies in the studied area describe the drainage systems and could potentially help to place new well positions to get maximum recovery of hydrocarbon with minimum risk.

Correlation and mapping of the maximum flooding surfaces show that the sequences are mainly sigmoidal-shaped wedges with distorted thickness distributions in the depositional-dip direction. The inherited topography controls the orientation of the Upper Jurassic successions, the turbidite complexes contain sediments mainly transported from west to east and occasionally south to north through a narrow conduit, involving significant axial transport.

The sand bodies thickness developments illustrate sediments partitioning within the sequences and are explained by the relationship between accommodations versus sediment supply in terms of mass-balance. In addition, onlap style and pinch-out character of the turbidite systems yield important information of sand deposition within the deep marine complexes. The mapping of these sequence-stratigraphic units serves as input to reservoir models.

Acknowledgment

This thesis has been carried out as a joint work with my fellow Maast Tom Erik at Department of Geosciences, University of Oslo under the supervision of Associate Professor Jens Jahren, Professor Knut Bjørlykke from the University of Oslo (UiO), Peter Keller (Advisor Geophysics) from Det norske (NOIL) and Ståle Monstad (Chief Geologist) from Det Norske Oileselskap ASA (DNO).

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Tanjina Islam

Oslo, September, 2008

Content

1 Introduction

The Late Jurassic is the most critical geological time interval of the North Sea and adjacent area's for intense rifting events which preserved the thick sedimentary successions in the graben area of the rift system. The study area of South Viking Graben is situated in the southern part of the Viking Graben, on the eastern edge of the East Shetland Platform. The area occupies a distinctive position following the main structural trend NNE-SSW.

The structural history of the region is very complex with several extensional and compressional episodes recorded. Tectonic activity occurred and the sea level fluctuation developed thirteen genetic stratigraphic sequences in the Upper Jurassic successions. These are bounded by maximum flooding surfaces. Sandstones with in the sequences show variation from marine to deep marine deposits and extremely variable thicknesses. To better understand the formation of the Gudrun discovery and other small discoveries in Upper Jurassic sand bodies are the motivation for this comprehensive semiregional study of this area to improve the understanding of the geometry, internal reservoir architecture, and quality of these sand bodies from both an exploration and exploitation point of view.

The main challenge in this study area is to establish the depositional model of the Upper Jurassic sandstones of the South Viking Graben. The origin and character of the deep water sediments depositional systems reflect a complex relationship between a range of controls including sea level fluctuations, basinal tectonics, the rate, type and nature of sediments supply. The connection between tectonics, surface tilting and facies geometry is perhaps the best understood in nonmarine basins (Leeder and Gawthorpe, 1987), but it is equally important in deep-marine basins where gravity-driven processes do respond to changing bathymetry by ongoing seabed deformation (Haughton, 2000).

This research work represent the genetic stratigraphic sequences scheme, descriptive facies system applicable to all Upper Jurassic sediments within the area combined with an indispensable biostratigraphic analysis, which has added significantly to make more accurate understanding of the sequences intervals.

Individual facies has been amalgamated into facies associations and the distribution of these facies associations have been used to propose a depositional model for the area. The model recognizes the importance of Late Jurassic structure and consequently the effects of basin complex morphology upon the depositional regime. The aim of this thesis is to demonstrate the value in building a depositional model through the integration of seismic data, wire-line logs and core-data within a sequence-stratigraphic framework.

The Study Area

The South Viking Graben of the North Sea includes portions of Norway Quadrants 24, 15, 16 and 9 (UK sector). The study area is located in longitude 58º45″ to 59º15″ N and latitude 01º25″ to 02º20″ E (Figure 1.1). The reservoir rock in Late Jurassic is mainly Intra Draupne Formation sandstones. The source rocks for this area are mainly Upper Jurassic Heather and Draupne Formations (Field, 1985, Isaksen and Ledje, 2001, Justwan, et al., 2005).

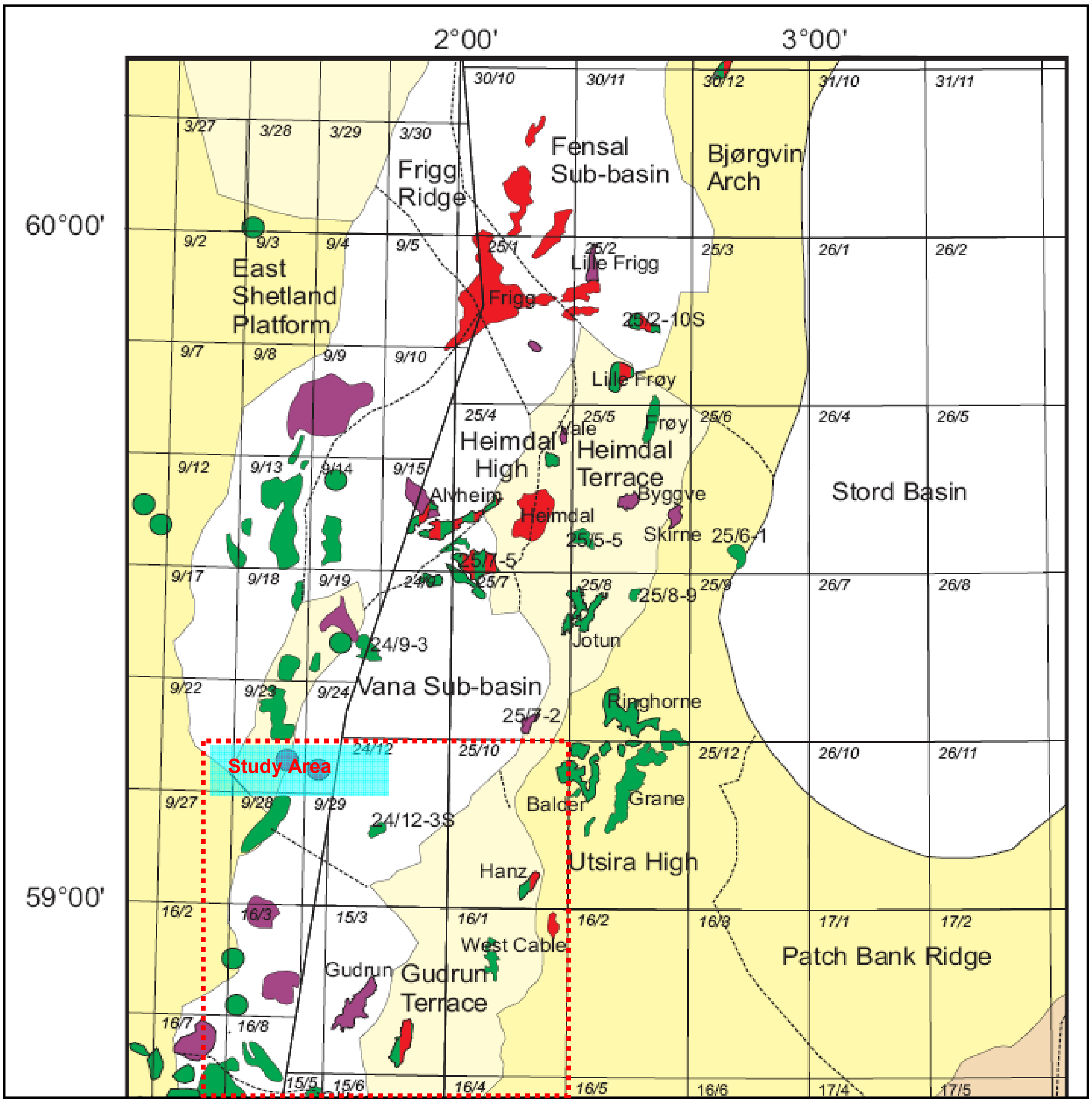

Figure 1.1 Study area locations and outline map of the South Viking Graben area displaying all major fields and discoveries as well as structural elements. Circular features in the UK sector indicate discoveries with unknown extent. The study area is showing by red box (Justwan, 2006).

2 Geological Setting

The study area is found in the South Viking Graben situated between the east flank of the East Shetland platform and the west of the Utsira High. The whole Upper Jurassic package is rapidly thinning towards the Gudrun Terrace and is absent on the Utsira High.

The structural, tectonic and stratigraphic framework of the Viking Graben and surrounding area is complex. Individual sub-basins are defined by differences in structural style and in the age of their prevailing sedimentary fill (Figure 2.1).

2.1 Structural Elements

The main structural elements of the study area are the South Viking Graben, the Utsira High, the Vana sub-basin, the Vilje sub-basin, the Gudrun Terrace, the Gudrun Structure and the East Shetland Platform. The following presentations of the structural elements are based on different studies.

South Viking Graben

South Viking Graben is an asymmetric graben bounded by a major fault against the East Sheetland platform in the west and it consists of a step-like feature that formed the Gudrun and Sleipner terraces in the east (Cockings, et al., 1992). The Utsira High is the final boundary of the graben on its eastern side (Figure 2.1).

The Viking Graben development began with the rifting and thermal subsidence in Permo-Triassic time (Underhill, 1998) related to the reactivation of Permo- Triassic structures (Faerseth, 1996). The major phase of the structuring of the northward trending graben system comprises the formation of five NNE trending half-graben elements arranged in a left stepping, enechelon pattern (Fraser, et al., 2002) taking place between the Late Jurassic and the Early Cretaceous, after it abated gradually (Ziegler and Van-Hoorn, 1989).

Utsira High

The area Utsira High is located within the southern part of quadrants 24 and 25 and the northern part of quadrants 15 and 16 in the North Sea (Figure 2.1). The structure is bounded by the Viking Graben to the west and the Stord Basin to the east. During the Triassic time it was most likely to be a topographic high (Steel & Ryseth, 1990). Because of the Crustal thinning of the Triassic strata and the erosion through Jurassic to Early Cretaceous time, Utsira high was thinned towards the east (Færseth, 1996). The present structural configuration is the result of extensional tectonism that occurred in the late Paleozoic and Mesozoic time (Isaksen, and Ledje, 2001).

East Shetland Platform

The East Shetland platform is the western limit of the South Viking Graben (Figure 2.1). This structure was developed during Mesozoic time (Zanella, Coward and McGrandle, 2003). The main faulting of the East Shetland platform was probably initiated during Devonian time. From Mid to Late Carboniferous, there were tectonic inversions (Coward, et al., 1989; Coward, 1993, Roberts, et al., 1999) causing large fault related structure on the East Shetland platform area (Serrane, 1992). During Jurassic upliftment the sediments of the East Shetland platform were eroded and transported into the South Viking graben and other adjacent basin areas.

Gudrun Structure

The Gudrun structure is relatively well defined both as an Upper Jurassic anticline and as a Middle Jurassic horst. The Gudrun structure is located in the Vilje sub-basin just west of the Gudrun Terrace and is an inversion structure (Figure 2.1). A thick Upper Jurassic clastic package is deposited in the half graben of the Vilje sub-basin. The inversions of the Gudrun structure were initiated during the Late Volgian period.

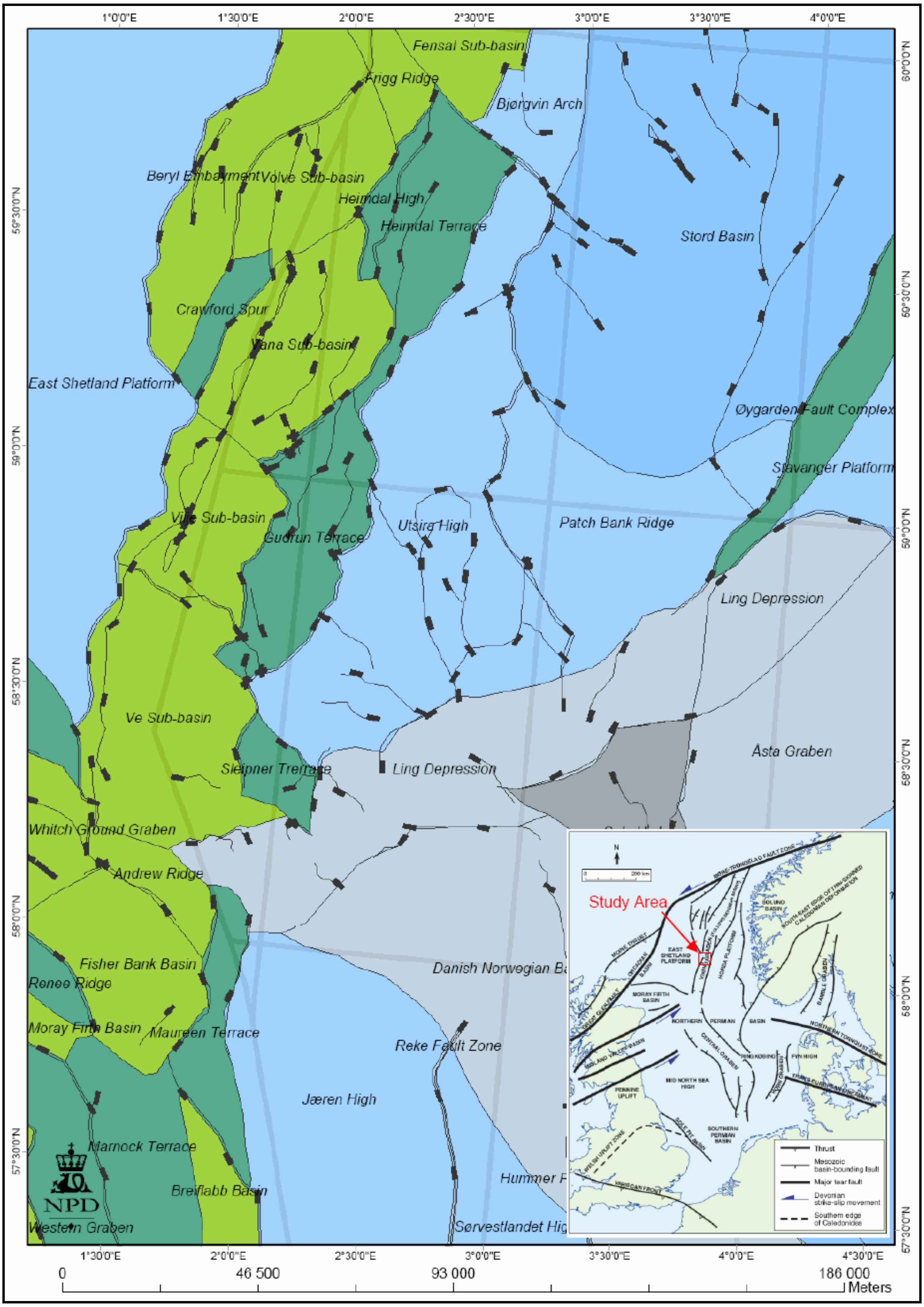

Figure 2.1 Structural and Tectonic elements of the South Viking Graben and its surrounding area (NPD, 2008) and study area location showing on generalized tectonic map of northeast Europe.

Vilje and Vana sub-basin

The Vilje and Vana sub-basin are located between the East Shetland Platform and the Gudrun terrace (Figure 2.1). These half graben basins were filled with thick Upper Jurassic deposits. The structures are bounded by a major fault against the west as well as by pace-like feature that formed Gudrun and Heimdal terrace in the east.

2.2 Structural and Tectonic Development

Evolution of South Viking Graben was mainly contributed by the Late Jurassic to Early Cretaceous rifting events which were developed in today's North Sea area. This was superimposed on earlier rifting which started during the Permo Triassic break up of the super continent Pangea developing a multidirectional rift system (Ziegler, 1988, 1990, Coward, 1995). The basin was filled with Cretaceous and Cenozoic post rift sediments sufficient to mature the Upper Jurrasic source rocks.

2.2.1 Permian evolution

During Early Permian Volcanism Northern England, the Midland Valley in Scotland, Southern Scandinavia and north-east Germany were affected by Westphalian inversions (Francis, 1987).

Permian and Triassic rifting was accompanied by ample sediment supply from uplifted areas and sedimentation kept pace with subsidence so that continental conditions prevailed in a desert environment (Figure 2.2).

2.2.2 Triassic Evolution

During early Triassic time the Arctic rift system continued to affect the north –west European region. During mid-Triassic the rift system was linked to western Tethys. The Atlantic rift system was dominated by faulting in western Britain and a part of western Ireland during Late Triassic time. North-west Europe was affected by mosaic fault block with two dominant northwest-southeast and northeast-southwest rift orientation (Coward, et al., 2003). These may signify the effects of a triple junction created by interference of the Arctic and Atlantic rift systems with extension in slightly different directions (Figure 2.2).

2.2.3 Jurassic Evolution

Early to Middle Jurassic Evolution

During early Jurassic minor rifting activities prevailed in the Northern North Sea. Callovian volcanics indicate the presence of a mantle hot spot in the northern North Sea during that time. Uplift associated with the hot spot caused (Underhill and Partington, 1993) erosion of the Lower Triassic strata in the central North Sea (Coward, et al., 2003).

Crustal extension began in the northern Viking Graben (Figure 2.2 and 2.3) during deposition of the deltaic sediments of the Brent Group in Bathonian time along with thickness and facies changes across newly developed north to north-easterly trending faults (Coward, et al., 2003).The rotating fault blocks of the South Viking Graben were initiated at this time (Rattey and Hayward, 1993). Erosion of Lower Jurassic sediments from the west of Shetland was also associated with renewed extension (Morton, 1992).

Middle to Late Jurassic Evolution

The Late Jurassic rifting in the South Viking Graben area is the most important tectonic event of the area because the basic structural framework of the North Sea basin was established during that time. Comparatively small amounts of extension had begun in the Viking Graben through Bajocian to Bathonian times. Over Callovian to early Kimmeridgian the rifting in the Arctic extended into the North Sea, forming north to north-easterly trending normal faults and north-westerly trending tear and transfer faults in the Viking Graben (Coward, et al., 2003). Continued extension occurred during Oxfordian in the northern North Sea, parts of the mid-Norway shelf and in the Viking graben area.

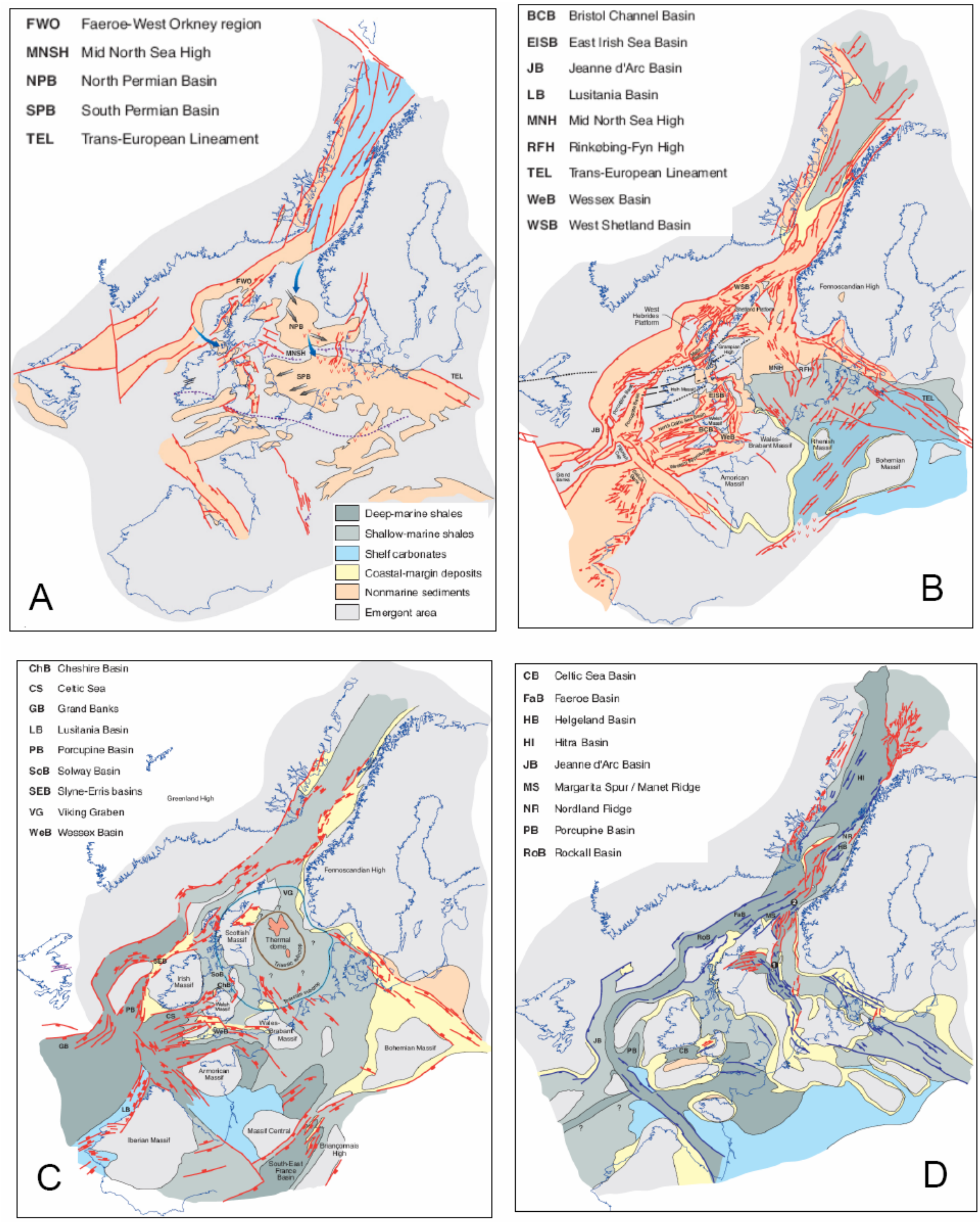

Figure 2.2 Showing the tectonic evolution of the south Viking graben and its surrounding area of A)Permian B)Triassic C)Early to Middle Jurassic and D) Late Jurassic time (Coward, et al., 2003)

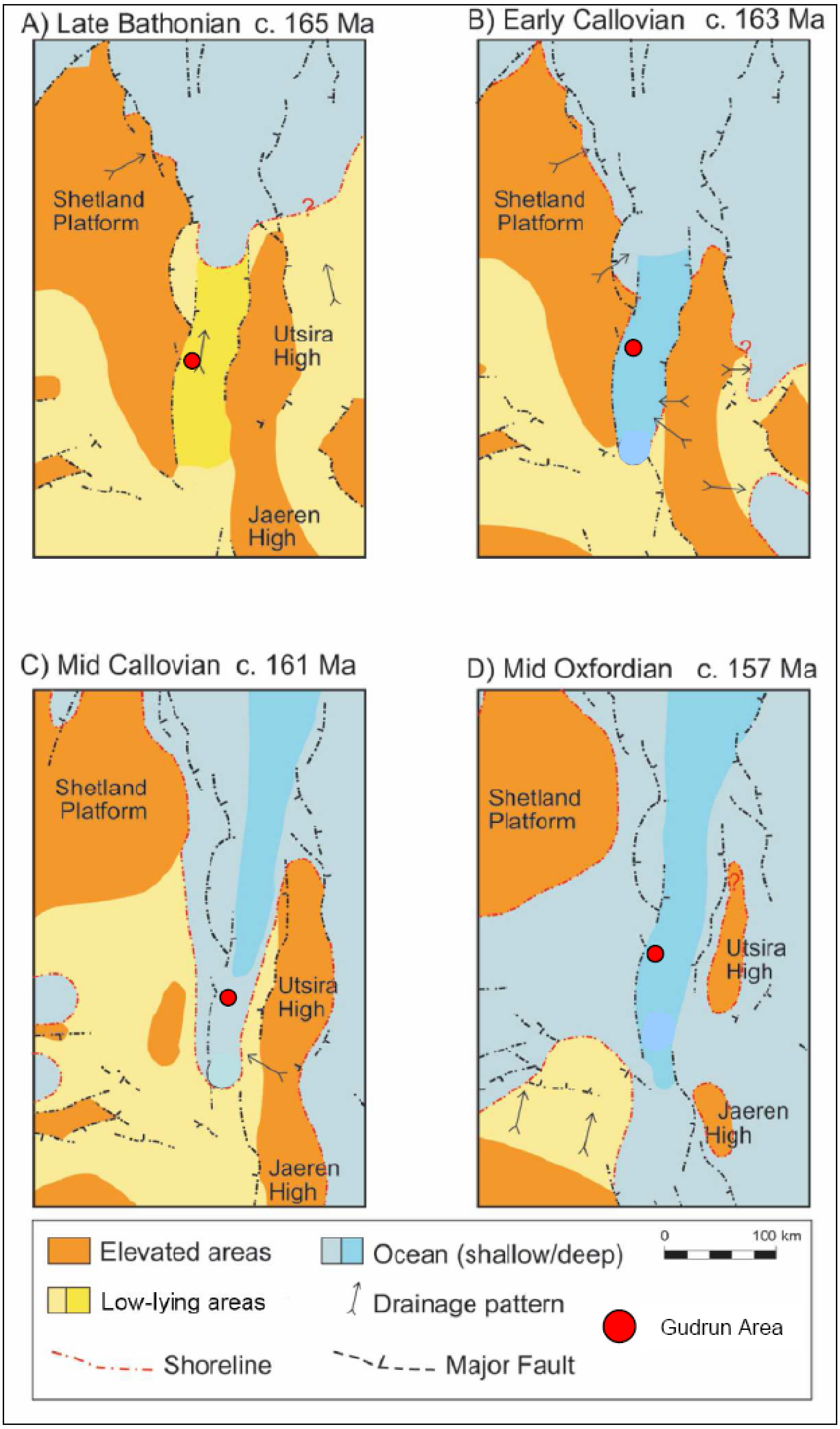

Figure 2.3 Showing tectono-stratigraphical development of the Viking Graben from Late Bathonian (A) to Mid Oxfordian (D) times. The location of the Gudrun area is highlighted. These maps illustrate the changes from alluvial to shallow marine to deep marine sedimentation in the study area through this time period as subsidence in the Viking Graben continued with flooding (Atle Folkestad and Nicholas Satur, 2008).

There were several phasess of faulting divided by major stages of relative tectonic quiescence providing a fundamental control on sedimentation in the North Sea area. The central North Sea was subjected to north-east to south-west directed extension across the Trans-European Lineament On late Kimmeridgian to Volgian time (Roberts, Yielding and Badley, 1990). In the Outer Moray Firth Basin and the Viking Graben, west-northwesterly trending normal faults, coupled with Volgian and Early Cretaceous extension, were superimposed on the north-easterly trending Late Jurassic normal faults (Coward, et al., 2003).

Viking Graben acted as a left-lateral transfer system among the north-east to south-west extension in the Central Graben and the rifting along the present Norwegian margin.

In the south Viking Graben earlier formed fault blocks were rotated causing local compressional inversions on the basin margins (Coward, et al., 2003). It formulated erosion of uplifted blocks and deposition of the Draupne and Heather Formations in the South Viking graben area in Late Jurassic time. These Formations are organically very rich and act as source rocks. Within these source rocks some thief sand bodies were developed. These sand bodies could be good reservoir units. To identify these sand bodies are one of the key elements of this thesis.

2.2.4 Cretaceous Evolution

Normal faults were still active during the earliest Cretaceous time in the central and northern North Sea associated with deposition of clastic sediments against the fault scarps. During early Cretaceous-Jurassic extension ceased with the onset of passive thermal subsidence and the syn-rift topography was covered by transgressive sediments to develop the Base Cretaceous boundary. Marine shale deposition predominated; the uplifted footwalls were gradually onlapped and covered, though there were numerous phases of minor fault reactivation, possibly due to compaction of earlier sediments (Coward, et al., 2003).

2.2.5 Paleocene to Recent evolution

Back-stripped wells in the North Sea and Faeroe–Shetland Basin demonstrate anomalous subsidence partially attributed to igneous underplating (White and Latin, 1993) during the

Paleocene. Uplift of northern Scotland probably associated with the Iceland plume, led to extensive erosion and to the deposition of submarine-fans in the North Sea and west of Shetland (Zanella, Coward and McGrandle, 2003).

Through Eocene to Oligocene the North Atlantic Ocean was formed between Greenland and Scotland. During Oligocene, the Labrador Sea ceased opening and there was a minor change in opening trend in the North Atlantic. Consequently, compression affected parts of large transform faults caused local inversion (Doré, et al., 1999).Basin inversion affected offshore Norway and minor inversion affected parts of the north-eastern North Sea.

During Pleistocene, Glacial erosion of the uplifted region of onshore Norway extended offshore (Riis, 1996). This created a well-defined glacial unconformity and developed the Norwegian Channel (Sejrup, et al., 1996).

2.3 Stratigraphy

Sedimentary successions of the Viking Graben area were developed from the Late Palaeozoic to the Cenozoic. The three oldest unconformities of Late Early Permian, Mid-Triassic and Late Mid-Jurassic age are identified in the study area. The Early Tertiary development is also characterized by non-depositional and erosional events (Figure 2.5).

The South Viking Graben is an asymmetric rift graben influenced by two major periods of extension during Permo- Triassic and Middle-Upper Jurassic age. The graben is flanked by the East Shetland Platform in the west and Utsira high to the east. The oldest sediments in the study area are found in Well 25/10-2R of Permian age (Isaksen, et al., 2002). Aeolian and evaporitic sediments were deposited in the study area during this period (Ziegler, 1992).

The South Viking Graben was affected by the first phase of extension during the transition period of Permian to Triassic (Færseth, 1996). During Triassic, Clastic sediments were deposited in arid to semi-arid climates in intra-continental basins (Fisher and Mudge, 1998), such as the sandy alluvial fan deposits of the Skagerrak Formation and the arenaceous mudstones of the Lower Triassic Smith Bank Formation (Goldsmith, Hudson and Van Veen, 2003).

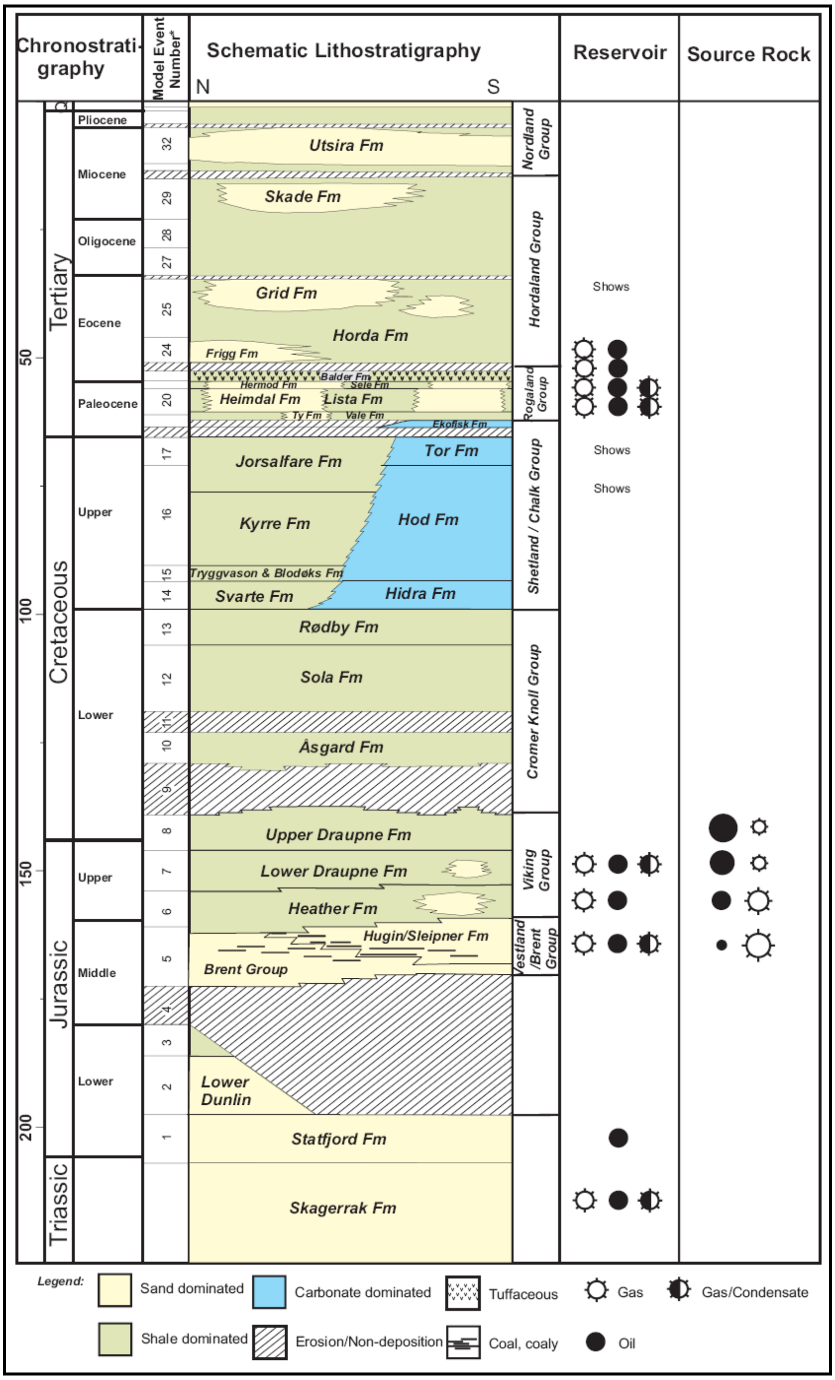

Figure 2.4 Generalized stratigraphic column for the South Viking Graben (Justwan, Dahl and Isaksen, 2006).

Deposition of the Statfjord (predominantly composed of sandstone) formation through Triassic to Jurassic periods record the transition from a continental through a marginal marine to the marine environments of the overlying Dunlin Group (Goldsmith, Hudson and Van Veen , 2003).

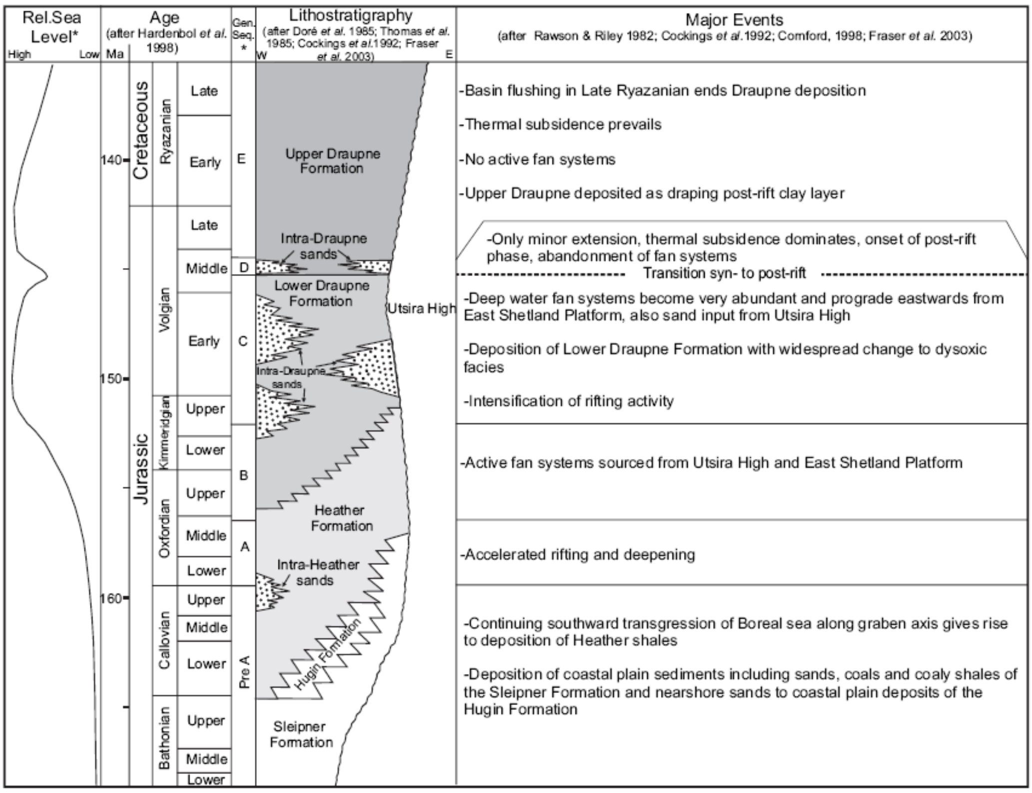

Figure 2.5 Showing major geological events of the Upper to Middle Jurassic succession, South Viking Graben (Justwan,et al., 2005).

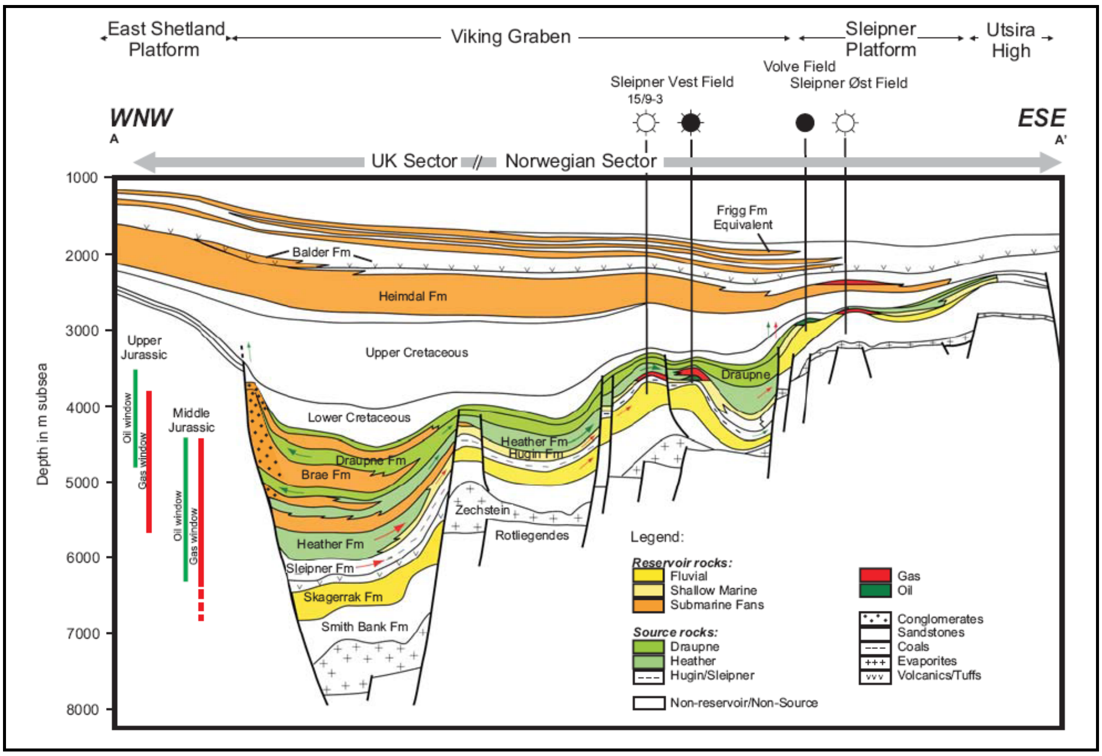

Figure 2.6 Schematic structural WNW-ESE cross-section displaying principal source and reservoir rocks and general structure of the South Viking Graben (Justwan, Dahl and Isaksen, 2006).

The second stage of rifting commenced in the Late Toarcian with uplift at the triple junction of the Central, Viking and Witch Ground Grabens. During this period, uplift caused significant erosion of the underlying sediments. Marine sediments of the Dunlin Group are therefore thin at south of 59° N in the study area (Skarpnes, et al., 1980). The Dunlin Group was deposited during Lower Jurassic period. Uplift caused by doming and associated erosion led to redeposition of sediments and the formation of the Brent Delta in the study area (Graue, et al., 1987).

Over the latest Bajocian to earliest Bathonian, sea-level rise caused the retreat of the delta resulting in the deposition of the Vestland Group together with the coal bearing coastal plain sediments of the Sleipner Formation and the overlying shallow marine to fluviodeltaic deposits of the Hugin Formation (Figure 2.5) (Rattey and Hayward, 1993).

Continued sea-level rise during the Jurassic rifting episode led to the deposition of the Heather and Draupne Formations (Figure 2.4 & 2.5) (Goff, 1983, Field, 1985, Cornford, 1998) holding a series of sand sheds as deep marine fans or slope aprons from the surrounding highs (Figure 2.5) (Justwan, Dahl and Isaksen,2006).

These sandy systems disappeared after termination of the rifting during the Middle Volgian and the upper section of the Draupne Formation was deposited as a draping clay layer in the area (Justwan, Dahl and Isaksen,2006) (Figure 2.5 & 2.6).

The Cretaceous deposits are mainly mud prone with some Carbonate intervals during the Late Cretaceous (Oakman and Partington, 1998) (Figure 2.4).

Uplift and erosion of the East Shetland Platform led to the development of the Paleocene and Eocene Submarine fans forming Frigg, Balder and Heimdal Formations (Figure 2.4) of the Rogland Group (Justwan, Dahl and Isaksen, 2006).

Three further episodes of uplift, erosion and consequent deposition of sand-rich units are recorded in the Oligocene and Miocene time (Rundberg and Eidvin, 2005). Pliocene sediments were deposited as uplift of the Scotland Shetland area. The Quaternary was subjugated by high subsidence rates reaching up to 300 m/Ma and deposition of glaciomarine sediments (Justwan, Dahl and Isaksen, 2006).

3 Data and Methods

Geophysical and geological data and methods used in this study are presented in this chapter. The seismic data includes seismic reflection survey (2D & 3D) and the well data includes well cores, logs and bio-stratigraphy.

The study of a sedimentary system requires many observation techniques, each of which can only provide information on one part of the entire depositional system. As a consequence, this study has combined different geophysical evaluation to develop a suitable depositional model (Figure 3.1).

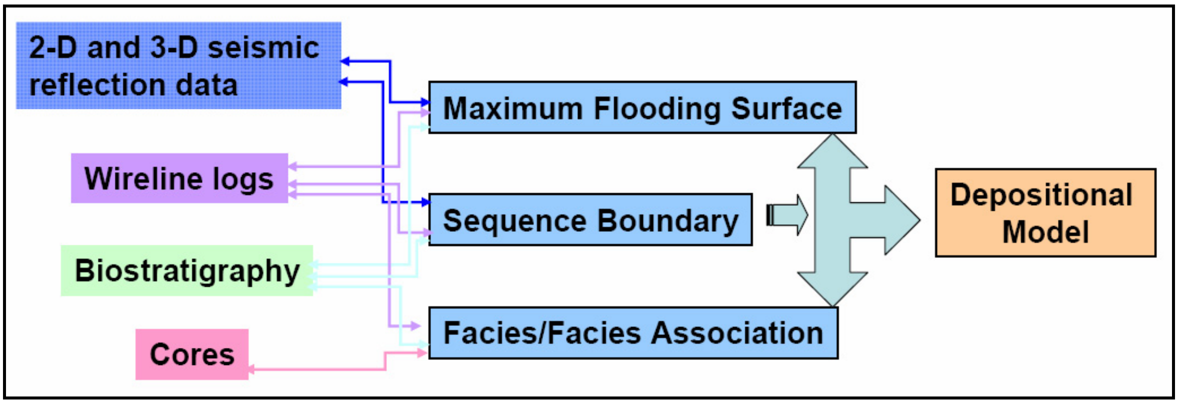

Figure 3.1 Flowchart showing the different data types used in the study area, their relevance and output.

3.1 Well Data

Most of the wells drilled on the study area to date have targeted traps in Jurassic tilted fault blocks. A comprehensive wire-line-log suite exists for most of the wells but only a minority of the wells have Upper Jurassic cores.

3.1.1 Well Interpretation

This study is based upon description and interpretation of cores from the three wells and interpretation of wire-line logs from ten wells in the South Viking graben area. Several facies associations have been identified based upon lithology, primary sedimentary structures, colour and bedding contacts with overlying and underlying units. Existing biostratigraphic analysis was consulted for consistency with the identified key sequence-stratigraphic surfaces.

To construct the depositional model, well correlation is the first key to sketch the boundary of different formation and sequence. Gamma and sonic log are used in this study for well lithology recognition and correlation. Generally same pattern of log curves are assumed as a same sequence and special pattern marked as maximum flooding surfaces but biostratigraphic information was used as a key control end.

Wells for core description

Well 15/3-3 (Vilje sub basin), well 16/1-5, well 16/1-5A (Gudrun Terrace) and UK 9/24b-4 (Vana sub basin) have been used for detailed core logging. The logging builds up the idea of the small scale sedimentary structures which give the facies information of the area.

Additional wells of relevance/importance

Wells 15/3-1S, 15/3-5, 15/3-7, 15/3-2, 16/1-2, 24/12-1R and 24/12-2T2 were used for well correlation using the Petrel well correlation software.

Additional database

Completion report for wells 15/3-5, 15/3-2, 24/12-1R, 24/12-2T2, 15/3-7, 15/3-1S, 16/1-2, 16/1-5, 15/3-3 and well report of well 9/24-b4 were used for detailed formation tops, cores information and other reservoir properties.

Internal DNO biostratigraphic reports for well 15/3-7, 15/3-2, 15/3-5, 16/1-2, 16/1-5, 24/12-1R and 24/12-2T2 were used for maximum flooding surface and sequence boundary identification. During well correlation, Facies Map Browser (FMB2) software was also used for sequence boundary and time interval recognition.

3.2 Seismic Data

As the study area covers several 2D and 3D seismic survey (Table 3.1), nearly 32 seismic surveys are fractionally used to interpret the top of the Upper Jurassic surface (Base Cretaceous). For Upper Jurassic sequences interpretation, three seismic sections have been selected. Selected seismic sections are AA`, BB` and CC` (Figure 3.2). A few of the more important survey names used for the Upper Jurassic sequences interpretation are mentioned below in table 3.1.

Table 3.1 Lists of used seismic survey in this study

Seismic 3D Survey	Seismic 2D Survey
CNS-Mega-ho 7	ST 9511
CNS-Mega-ho 8	SNST 3D
CNS-Mega-ho 7	NH 9301R97
CNS-Mega-ho 8	F19501
WGS-24-12 new	CN2593
CNS Mega	

3.2.1 Seismic Interpretation

Seismic interpretations of the selected sections and surface were prepared to see the horizontal facies distribution of the study area. In this study seismic interpretations were performed to get additional support for well correlations. Seismic interpretation helps to infer the continuation of the maximum flooding surface which is usually identified by the onlapping response in the seismic section in deep marine sediments. The sediments within two maximum flooding surfaces develop a sequence called genetic stratigraphic sequence. In this study the main attention is given to onlapping surfaces which normally carry markable sand having the potential to be a good reservoir (Figure 3.3).

There is no particular characteristic seismic reflection property that provides a unique guide to the recognition of individual facies. For example, continuous flat-lying reflections may reflect deep-marine shale, coastal-plain topset, alluvial plain or lacustrine facies. However, a seismic facies map may be used to construct one or more geological models,which should ideally be calibrated by well control.

The seismic interpretation presented here is done by using Kingdom 8.2 tool (Figure 3.2 for location of seismic lines). The interpretation focuses on examples of unconformities and sediment wedges which are regarded as two of the major ingredients of sequence interpretation, one being erosional and the other depositional (Emery and Myers, 1996).

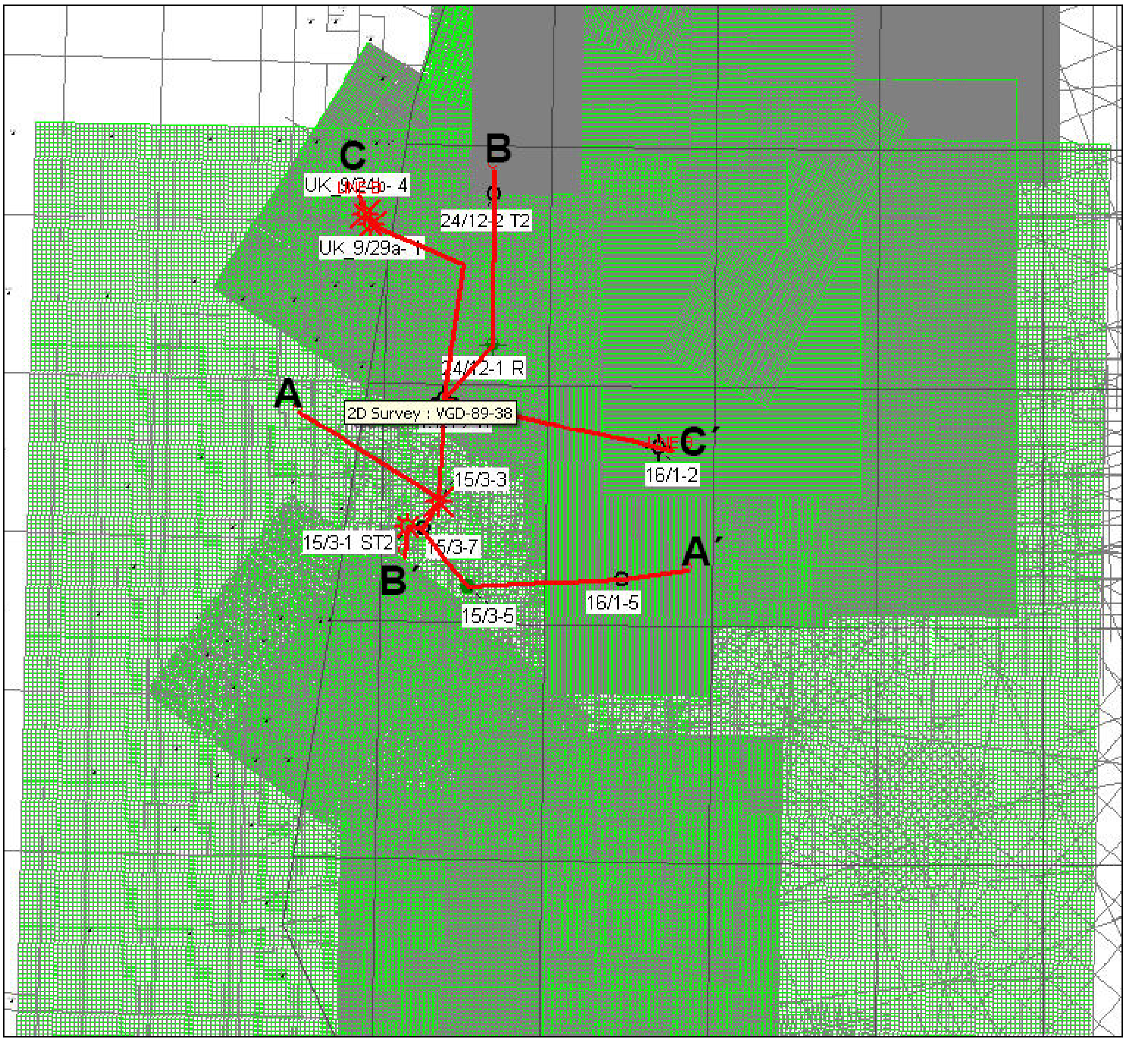

Figure 3.2 Map showing the seismic survey coverage in the study area and location of wells used for well correlations.

3.3 Facies Interpretation

For detailed facies interpretation, core logging was carried out and important sedimentary features on the core slab were identified. The surface of each sedimentary feature was carefully cleansed to obtain maximum information. Special features such as grain size progression, termination of sand lenses etc were carefully marked and photographs were also taken. Attempts were made to identify individual facies and sedimentary cycles. Structural surfaces of the sediment and its erosional surfaces were identified and the parts of depositional systems and pattern of the sequences were recognized.

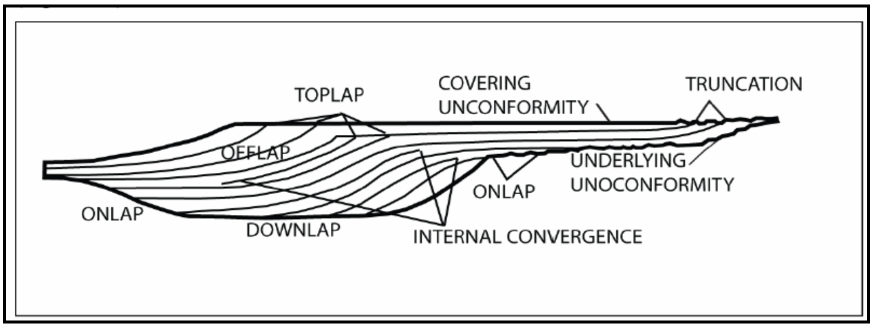

Figure 3.3 Seismic stratigraphic reflection terminations within idealized seismic sequence (redrawn from (Mitchum, Vail and Thompson, 1977).

From the vertical stacking pattern of the facies associations and their internal relationship, the facies associations have been grouped in to units. The vertical stacking pattern and lateral distribution of facies associations are the basis for the sequence-stratigraphic analysis in this study. Key sequence-stratigraphic surfaces with potential for semiregional correlations were identified from changes in the stacking pattern of the facies associations and discontinuities in cores and wire-line logs.

3.4 Depositional Model

Detailed facies association styles with sequence-stratigraphic interpretations have been constructed in north–south and east–west depositional directions. The final objective of this thesis work, i.e, to develop a depositional model for the Upper Jurassic reservoir rocks in the South Viking area has been constructed by combining all geophysical evaluation.

4 Seismic Interpretation

Seismic interpretation is presented in this chapter and illustrated by examples of interpreted seismic sections, type sections for each seismic sequence and time thickness contour maps of Base Cretaceous. This chapter presents the results of seismic sequence analysis together with the thickness and distribution of individual seismic sequences along the South Viking graben area. The seismic interpretation has mainly been done by using seismic interpretation tool Kingdom (SMT).

The upper Jurassic development of the South Viking graben area is very complicated for its complex geology which causes the interpretation of sediments succession in this area a challenging work. Both 3D and 2D seismic surveys are used for the interpretation of these deposits. Seismic interpretation of the area was carried out to determine the facies distribution, depositional pattern and probable sequences developments during the Upper Jurassic time. Well information was used from the NPD and Aceca (FMB) data sources and cross checked with available information provided by the oil company DNO (new name NOIL).

In the study area, thirteen Late Jurassic maximum flooding surfaces were identified within the Upper Jurassic succession. The identification is mainly based on logs and core interpretation. However, only ten of these sequences were possible to define from the perspective of seismic interpretation.

It is known that the seismic reflection depends on the multiplication of density and velocity of the layer. If the thickness of any layer is less than ¼ of the wave length (normally 25 m) of the seismic signal, that layer is not visible in the seismic, again if any layer contains more or less the same type of lithology, it will also not be distinctly differentiated in the seismic response. Thus all the interpreted J sequences cannot possibly be shown in the seismic section, nevertheless the important seismic responses are (thick sand body) shown in the study area along with few other which will help give the idea of overall distribution of the J sequences.

Base Cretaceous Interpretation

Firstly, the Base Cretaceous surface has been interpreted as it is the topmost horizon of the Late Jurassic deposits which is relatively easy to interpret. It gives an overall idea of structural and depositional pattern of the study area during the Upper Jurassic time. In the interpretation, dense grid (16 to 8 line increment) was taken considering the difficulty of interpretation caused by the complex geology and poor seismic resolution in the study area.

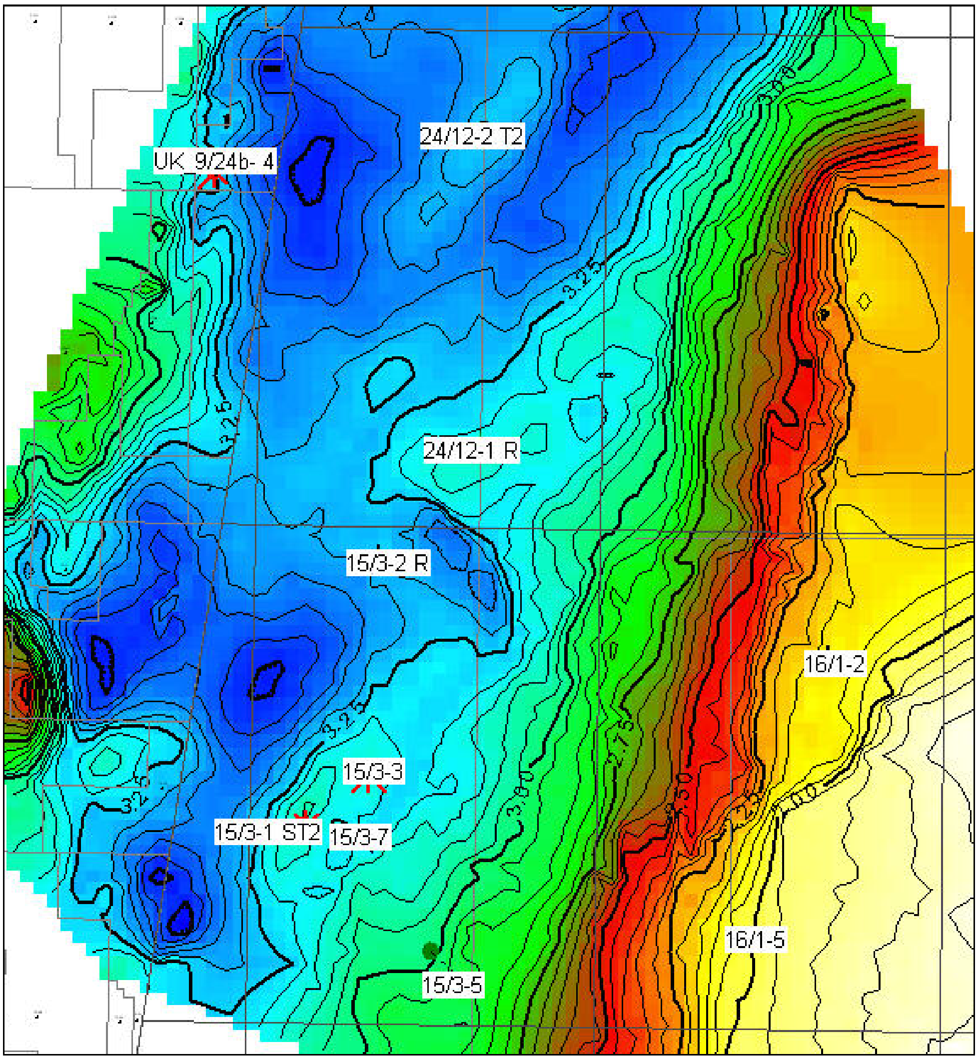

Figure 4.1 Showing Base Cretaceous time structure map of the study area.

The generated structural time contour maps illuminated the overall geology of the studied area at Base Cretaceous time. As the map reveals, the blue colour areas indicate the deepest part and the yellow colour areas indicate the higher topographic section of the area (Figure 4.1).

4.1 Type Sections

A type section is a seismic section or a line on which a particular surface is defined as a seismic sequence boundary and it is extended throughout the study area in a particular direction NS or EW. Three type sections have been chosen to present the seismic interpretation. The location of these type sections AA`, BB`, and CC` are shown in Figure 4.2. Two sections are taken in the east west direction and one in the north south direction. Base of Upper Jurassic is the oldest and Base Cretaceous is the youngest interpreted surfaces in the study area. Within those surfaces sequences J 46 to J73 are presented in ascending orders from bottom to top.

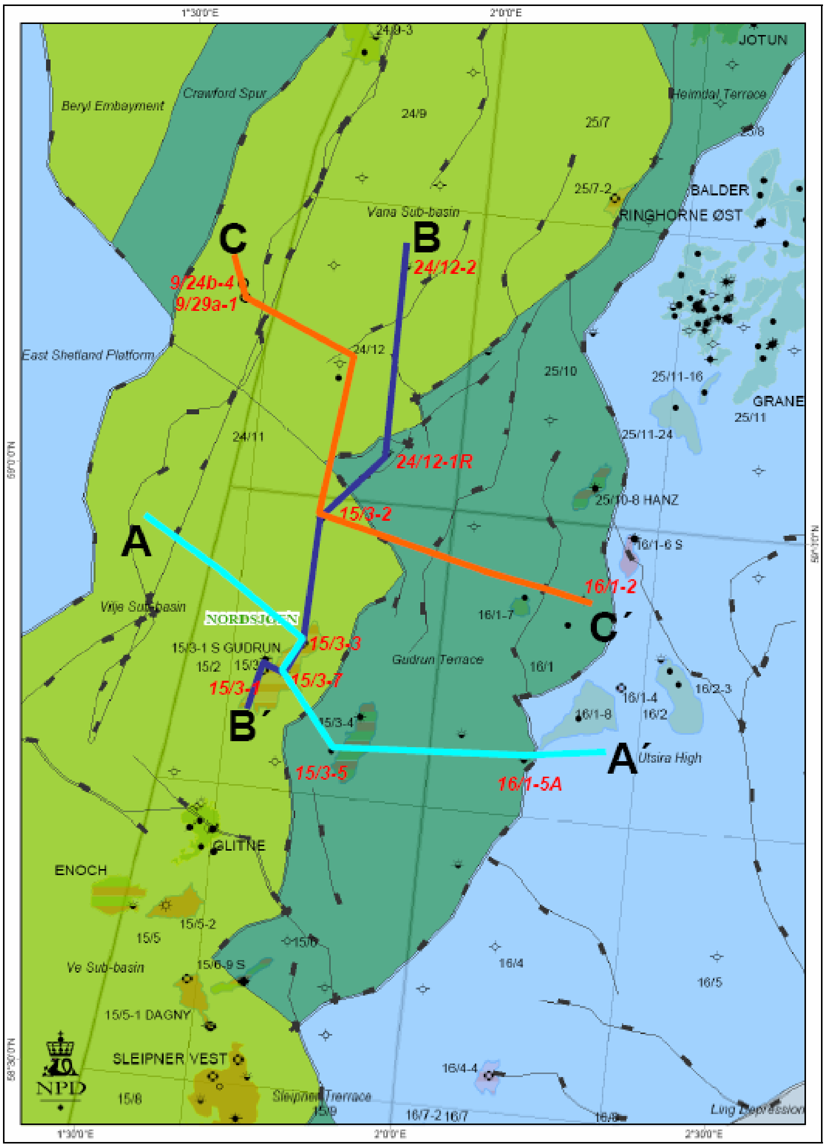

Figure 4.2 Map showing the location of the seismic type sections used in this study

4.1.1 Section AA′

An arbitrary line drawn with interpreted seismic sequences of the type section AA` is presented in Figure 4.3. The type section AA` is an arbitrary seismic line which draws on mutipule 3D cluster survey. This seismic section extends laterally up to 45 km from the westernmost margin in the Vilje sub-Basin to the easternmost part in the Gudrun Terrace (Figure 4.3).

The interpreted sequences J73, J72, J71, J66B, J66A, J64, J63 and J62 are shown in this section. Because all the surfaces are very well developed, these are relatively easy to differentiate in different seismic sequences, especially in the western part of the study area.

The line AA` has been selected as it passes through the interpreted 16/1-5, 15/3-5, 15/3-7 and 15/3-3 wells. In the interpreted section, it shows that most of the J sequences were continued in the Vilje Sub-basin with the thickness of each sequence being increased towards the western side.

The interpreted J sequences were onlap on the older maximum flooding surfaces indicative of the rising sea level. In the Gudrun terrace area the thickness of interpreted sequences J62 to J73 decreased remarkably and towards east sequences boundary was not possible to locate. The seismic resolution was also poor in that area to differentiate the J sequences but base and upper Jurassic boundary was possible to separate. Figure 4.3 also shows the presence and continuation of sand bodies within J 63 to J 66B sequences in Vilje-sub basin and also partly in Gudrun terrace.

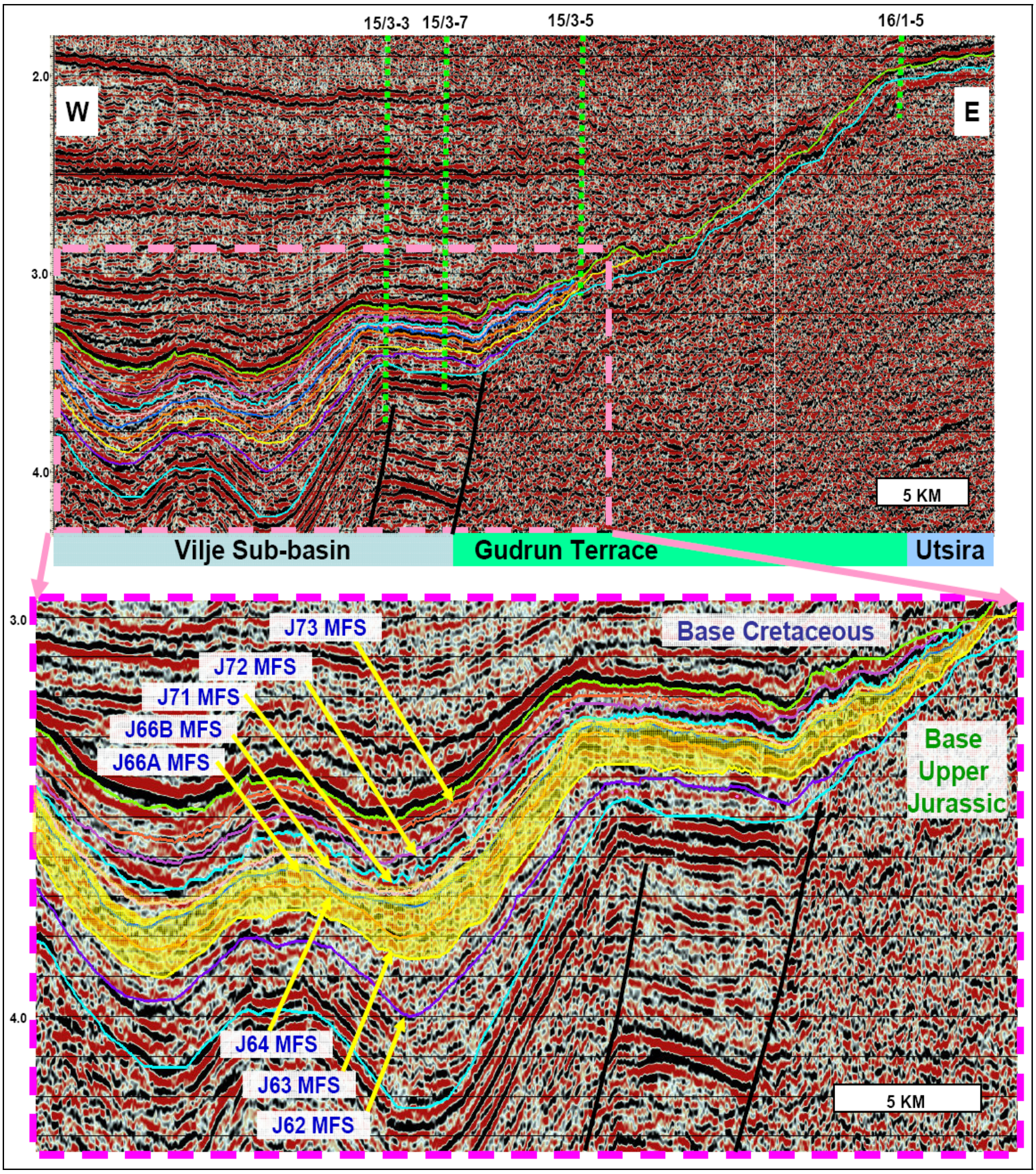

Figure 4.3 Type Section west to east AA´, see Figure 4.2 for line location. Upper part of figure shows Upper Jurassic sequence interpretation. The sequence became thinner towards the east and completely disappear further east in Gudrun Terrace area. Rectangle outlined in pink shows detailed seismic section with interpreted maximum flooding surface distribution between J73 and J62 (lower part of figure). Yellow marked area illustrates sand distribution in section. Onlap features of MFSs also striking towards east. Note the vertical section in second.

4.1.2 Section BB´

The north-south selected line BB` is shown in Figure 4.4. This seismic section extends laterally up to 50 km from the northernmost margin in the the Vana sub-basin to the southernmost part in the Vilje Sub basin.

The upper Jurassic sequences and sand bodies interpretation within sequences were done by correlation of seismic response (amplitude) and well logs contribution. The interpretation shows the south eastward thickening of the sand bodies and it indicates that towards north it was not possible to trace. The interpreted J sequences from J63 to J71 are onlap on the structurally high, central part of the section.

Seismically the correlation of the sand bearing sequences J63, J64, J66a and J66B are more visible in the southern part of the section near wells 15/3-3, 15/3-7 and 15/3-1S. It shows that the distribution of sand bodies were terminated towards the north as the sand carrying sequences were ended by the developing of onlap features above the sequence J62. Sand bearing sequences were again covered by mud dominated sequences in the same area. Here sand bodies can act as a reservoir rock whereas shale layer can act as a cap rock for accumulated hydrocarbon if it exists in the area. In the most northern part of the selected section near wells 24/12-2T2 and 24/12-1R, markable thick packages of sand bodies were not found. Probably the area was under erosion or there were no deposition of sand containing sequences during the time of their deposition probably because of faulting.

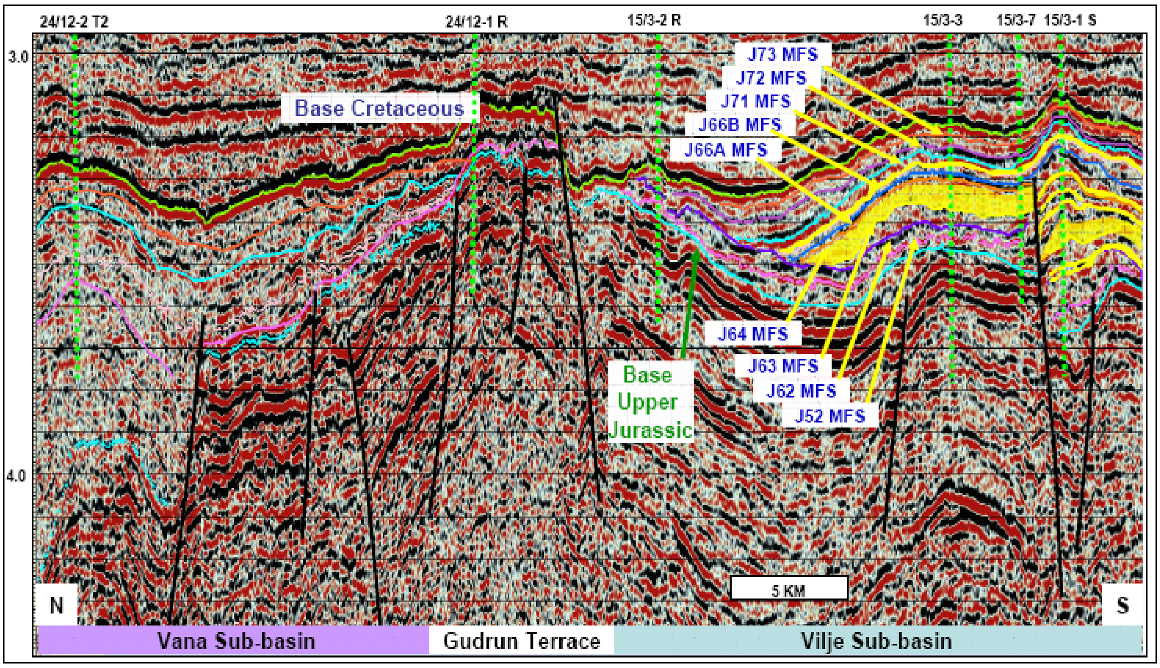

Figure 4.4 Type Section north to south BB´, see Figure 4.2 for line location. Seismic section shows maximum flooding surface distribution between J73 and J62. Yellow marked area illustrates sand distribution in section and onlap features of MFS. Note the vertical section in second.

4.1.3 Section CC´

It is already mentioned that the upper Jurassic South Viking Graben is a faulted area. It is really hard to get a complete seismic response from the area. This line CC´ was taken to get some additional support to understand the distribution of the upper Jurassic sequences.

The selected line CC´ lies in the east-west direction of the central part of the study area (Figure 4.5).This line has been chosen as it goes through the well 9/24-b4 in Vilje sub-basin to 15/3-2 in Vana sub-basin and 16/1-2 in the Gudrun terrace. In the western part, the J 63 sequence contains a thick sand body which gradually thinned towards the east and finally ended near the Vana Sub-basin. Here it also shows the onlap feature of the J sequence identified by the recognition of MFS from J64 to J72. However, the poor seismic response has rendered it impossible to map the sequence in the eastern part.

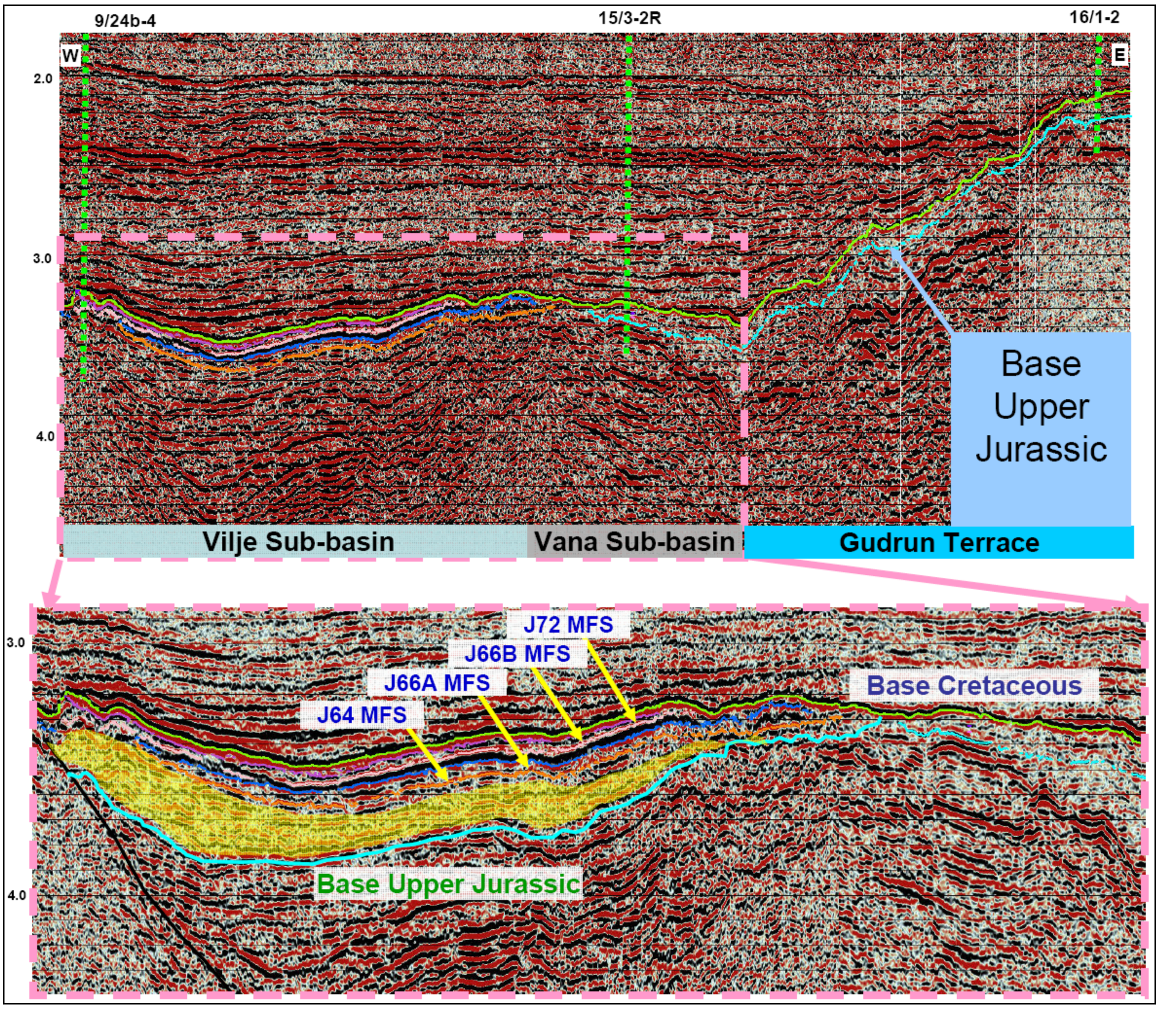

Figure 4.5 Type Section west to east CC´, see Figure 4.2 for line location. Upper part of figure shows Upper Jurassic sequence interpretation. The sequence became thinner towards the east and completely disappear further east in Gudrun Terrace area. Rectangle outlined in pink shows detailed seismic section with interpreted maximum flooding surface distribution between J73 and J62 (lower part of figure). Yellow marked area illustrates sand distribution in section. Note the vertical section in second.

5 Well Correlation

5.1 Introduction

Well correlation is presented in this chapter and illustrated by examples of interpreted maximum flooding surfaces (MFS) and correlation profiles (AA´ BB´ and CC´) through key wells of the study area (Figure 5.1). The chapter clarifies the identified sequences distribution together with their thickness along the South Viking Graben area. The well correlation has been done by using the Well correlation tool in Petrel.

South Viking Graben of the North Sea area was affected by Late Jurassic rifting developing many genetic stratigraphic sequences (Figure 5.2) (Galloway, 1989) which were bounded by maximum flooding surfaces (Partington, et. al., 1993). In well correlation those genetic stratigraphic sequences (J sequence) are selected by the recognition of the maximum flooding surfaces (MFS). These maximum flooding surfaces correlate from well to well by the help of biostratigraphic data, lithostratigraphic information and wire line log response in the study area. In general the probable result of closely spaced well correlation will be high-quality accuracy and a high degree of confidence. Large distance regional correlation can easily bring in errors as the wire line log response changes laterally.

For well correlation, 10 key wells have been used for correlating the wells for the Upper Jurassic genetic stratigraphic sequences identification of the study area. The selected wells are 15/3-3, 15/3-1S, 24/12-1R, 24/12-2T2, 16/1-5, 15/3-7, 15/3-5, 16/1-2 (Norwegian area) and 9/24-b4 (UK area). The selected wells help to find out the lithology, correlation of litho logs, facies identification and finally develop the depositional environment of the study area.

Well correlations in this chapter are presented by three profiles; two of them AA´ and CC´ are in the west to east direction; and the last BB´ is in the north to south direction through key wells of the study area (Figure 5.1).

In most of the studied wells, biostratigraphic analyses were performed largely based on core cuttings and side wall cores. The biostratigraphic zonation is based on palynology and microfossil study reports (based on Partington, 1993b) provided by DNO (NOIL new name).

In general gamma and sonic log are important tools for lithology interpretation. Generally a high gamma value indicates the presence of radioactive minerals common in shale or clay rich materials and a low gamma value indicates the presence of sand size particles. The Sonic log is used to measure both lithology and porosity of the formation by measuring the interval transit time passing through the formation. Generally high sonic value response indicates shale and less value for sand, limestone and dolomite.

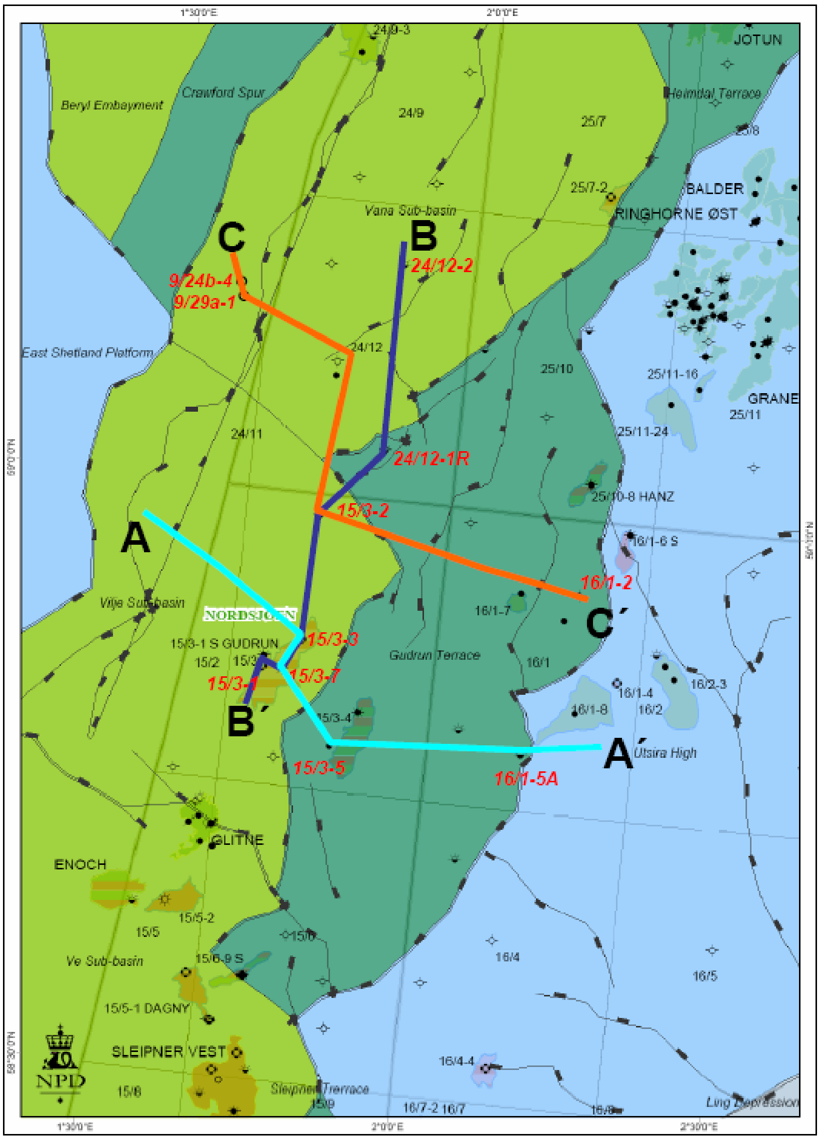

Figure 5.1 Showing the selected well in the study area with correlation profile.

5.2 Log Correlation

It is well known that the rifting was active during Late Jurassic in the North Sea area resulting in a highly faulted topography. The depositional sequences were also influenced by many small and large scale transgressions and regressions as functions of the sea level (Partington, et. al., 1993a) continued. Therefore in this study the well log interpretation is made primarily to focus on the maximum flooding surfaces. Mainly two types of flooding surfaces were identified during Late Jurassic rifting in the North Sea area:

1) Regular Maximum flooding surfaces
2) Tectonically enhanced maximum flooding surfaces.

Maximum flooding surface (MFS) represents a group of genetic stratal surfaces (described below) which are sequences bounded and which temporarily cover clastic source areas reducing clastic sedimentation in the basin center without any significant change of the basinal paleo geography (Partington, et. al., 1993a). (Figure 5.2).

Tectonically enhanced maximum flooding surface (TEMFS) was common in the Jurassic time in the North Sea area with its drowned footwall reducing the deposit of coarse clastic sediments in the basin center and marginal areas with different hanging and footwall stratigraphy. TEMFS shows retrogradational features in the hanging wall side whereas discrete condensed gamma ray spikes in the footwall (Partington, et. al., 1993a).

The Genetic stratigraphic sequence is “a package of sediment recording a significant episode of basin margin outbuilding & basin filling, bounded by periods of widespread basin margin flooding ”(Galloway, 1989) (Figure 5.2).

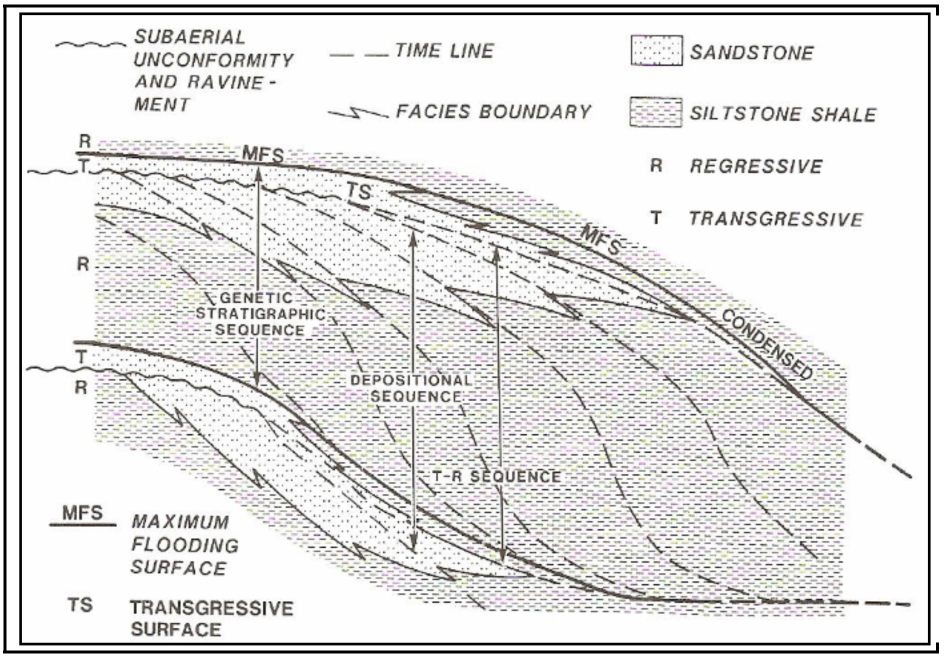

Figure 5.2 The Embry model, T-R sequence (Embry, 1993). The schematic stratigraphic section shows T-R sequence compared with boundaries of Exxon depositional sequence and Galloway`s genetic stratigraphic sequence. A genetic sequence stratigraphic sequence uses maximum flooding surface (MFS) as boundaries.

Both types of maximum flooding surfaces (as mentioned above) are often identified by the high gamma ray peak values normally separating the shale from its sand and silt. The MFS contains the most distal facies of the sequence. This result also matches with log response from sonic log which commonly also shows a high value. There are several high gamma ray peaks found in the Late Jurassic successions which are flooding surfaces rather than MFSs. To resolve this difficulty, biostratigraphic information is used to separate the MFS from the other flooding surfaces. So the initial work that started with wells have good biostratigraphic data and those wells were 24/12-2, 24/12-1, 15/3-2, 15/3-7, 15/3-5, 16/1-2 and 16/1-5. Maximum flooding surfaces were identified from these wells and then suitable information was used in other wells for further correlation of the entire study area.

After identifying the maximum flooding surfaces, the Genetic stratigraphic sequences were recognized to interpret the depositional environment of the selected sequences.

5.2.1 Biostratigraphic Calibration

Biostratigraphic calibration of condensed interval (Galloway, 1989, Loutit, Hardenbol and Vail, 1988) and sequence has been extensively used for the calibration of the marine condensed horizons/MFS. The rate of sedimentation in the North Sea during Late Jurassic time was low for a longer period of time. As such, the biostratigraphic zonation was dependant on the robust technique rather than abundance and diversity peaks (Fraser, et al., 2002, Partington, et al., 1993, Mitchum, Vail and Thompson, 1977). In the study area the Genetic stratigraphic sequences were figured out based on both biostratigraphic information (given by DNO) as well as log (gamma and sonic) responses from the selected wells (Figure 5.3)

5.3 Sequence Interpretation

Thirteen (13) maximum flooding surfaces were recognized (Figure 5.4) in the studied section representing the sequences J46, J52, J54A, J 54 B, J56, J62, J63, J64, J66 A,J 66 B, J71, J72, and J73 (following Partington ,et al., 1993b).

In log response, maximum flooding surfaces were marked by the increasing gamma and sonic value trend. Observation of the shape of the log curve also indicates the presence of depositional energy, lithofacies and finally the basin fill history during the time (Emery and Myers, 1996). Detailed descriptions of the identified different maximum flooding surfaces are summarizing below.

MFS J46 which is also known as the Upper Jurassic surface in this study is marked by high gamma and sonic value interval. This marker is identified in most of the selected wells in the South Viking Graben area. Above this surface, gamma ray increased very slowly until it reached MFS J52. The Genetic sequence J46 /Base of the Upper Jurassic sequence is recognized within the MFS J 46 to MFS J52 .The maximum thickness of the J46 sequence is found in wells 15/3-3, 15/3-7 and 15/3-1S in the Vilje sub-basin area. The thickness is around 40 m in these wells gradually decreasing in wells towards the east; in well 16/1-5 it is around 10m only. In the west in well 9/24-b4 this sequence is absent.

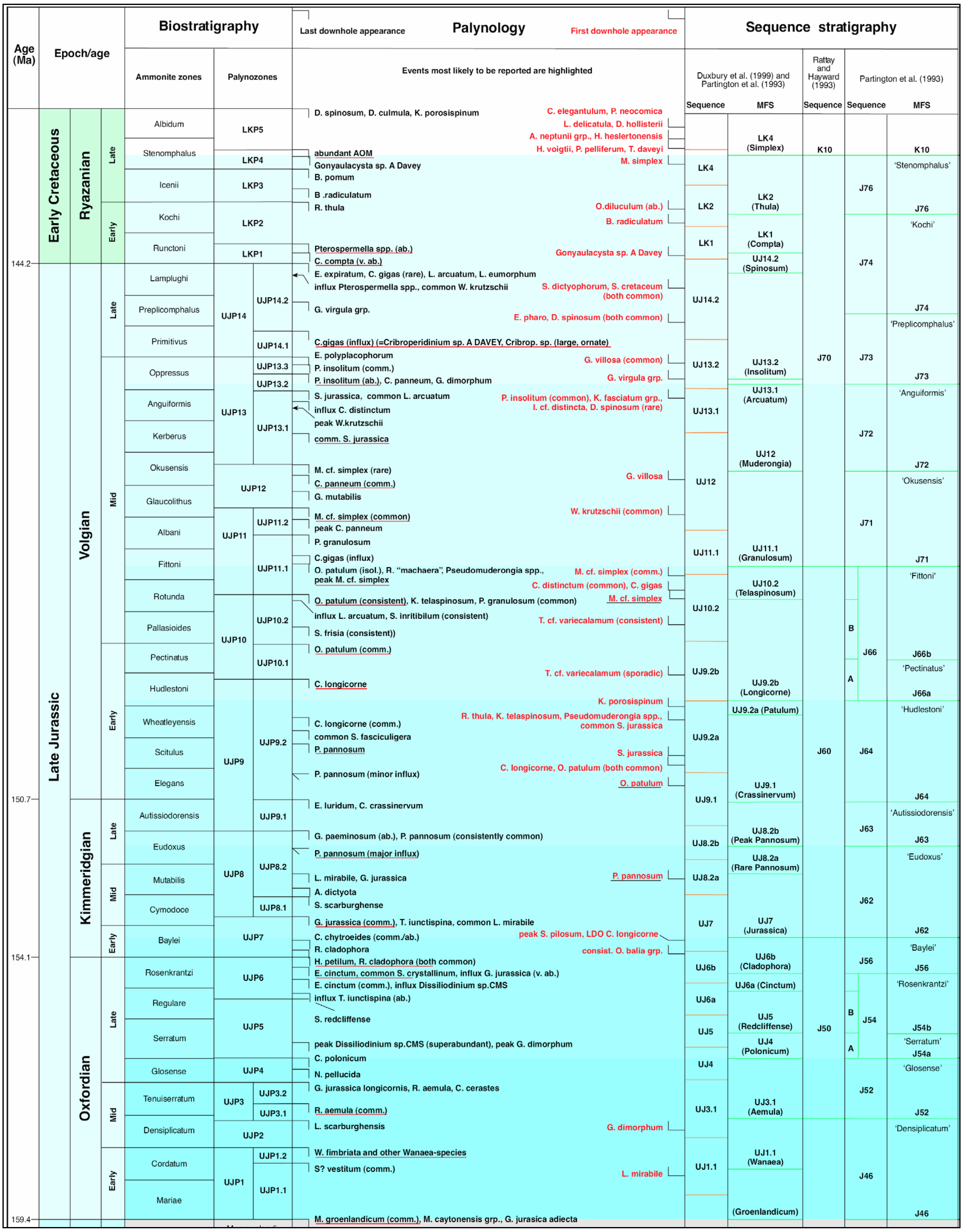

Figure 5.3 Upper Jurassic genetic sequence stratigraphy chart (Fraser et al. 2002).

MFS J54A shows high gamma ray peak in wells 15/3-3, 15/3-7 and 15/3-1S. There is a very close gap between J54A and J54B sequences. The maximum thickness of the J54A sequence is found near the well 16/1-5 (approximately 30m) but in the area near the Vilje sub basin in well 15/3-3 the average thickness of the sequence is 10m only.

During the deposition of this sequence the south central part of the study area was probably far away from the sediment source. Therefore very little sediments could be transported to the deep basin area during the deposition of this sequence.

MFS J54B is not found in the north western part of the study area. Probably the area was under erosion that caused it to fail to develop the maximum flooding surface near well 24/12-1R and 24/12-2T2.

The sequence J54B is characterized by the gradually decreasing gamma values upwards. The maximum thickness of the sequence near well 16/1-5 in the eastern part of the area is 25 to 30 m. The minimum thickness of the sequence is found near the Vilje sub basin where it is only 10 m in average in wells 15/3-7, 15/3-3 and 15/3-1S.

MFS J56 is recognized by high gamma and sonic values with a gradual decreasing trend upwards. The upper limit of the J56 sequence is marked by MFS J62.The average thickness of this sequence is almost the same in most of the wells and is around 20m with maximum thickness found in well 15/3-2 is above 40 m.

The sequences from J46 and J56 mainly contain gray to dark brown shale with a few limestone and sandstone stringers except in the well 16/1-5 where the sequences are dominated by coarse to fine grain sandstone with some granules (Figure 5.5) in it.

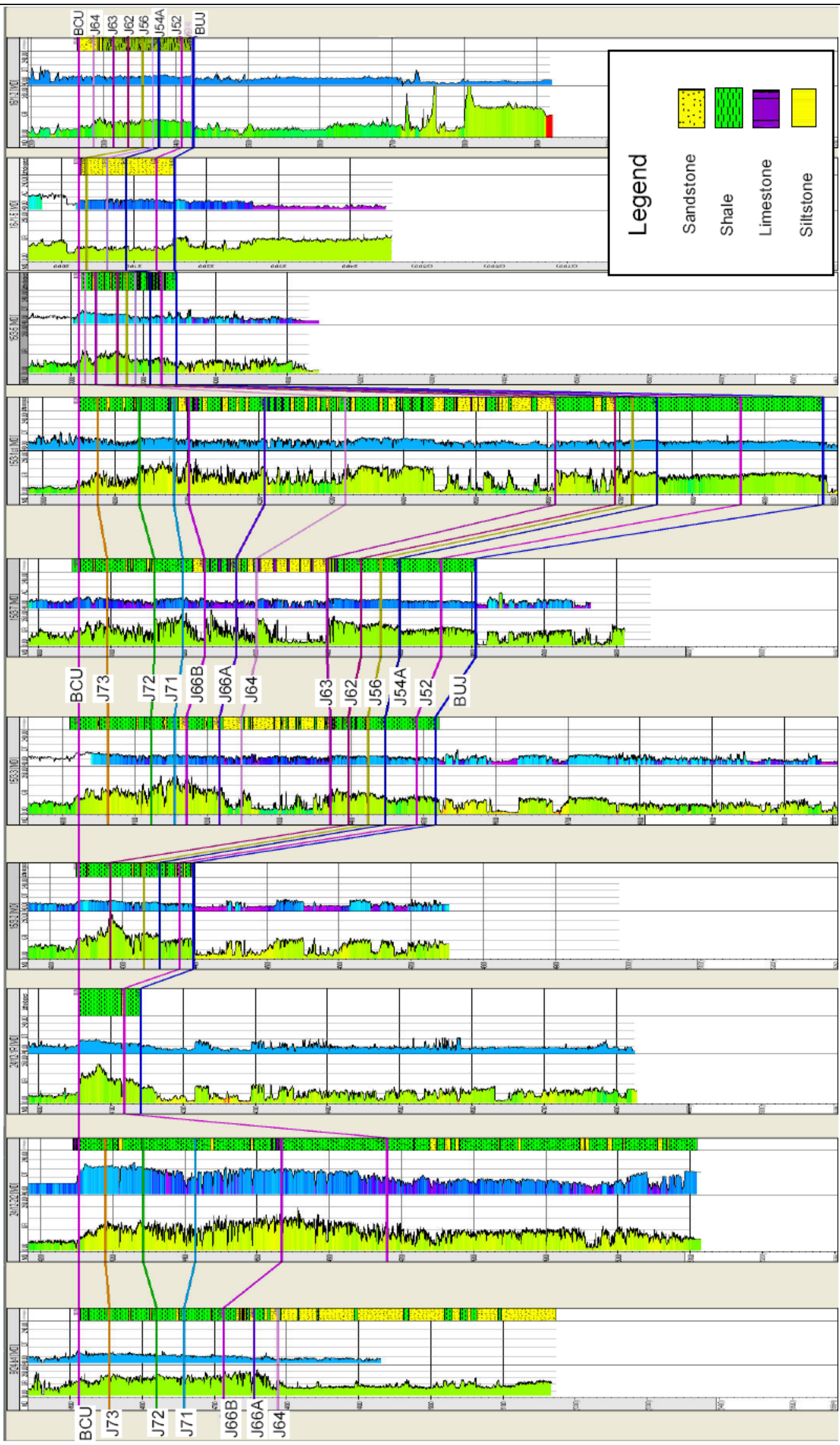

Figure 5.4 Well Correlation profile through key wells of Upper Jurassic interval (J52 – J73) flattened on top Base Cretaceous (BCU); GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

MFS J62 also shows high gamma and sonic values which are followed by a decreasing trend of the gamma value until it reached the next MFS J63 in most of the wells. Rapid fluctuation of the gamma values near well 15/3-1S indicates the influence of thin sand bodies in shale dominated sequence J62 (Figure 5.6).These sand bodies are normally compact, occasionally pyretic with alternating shale layers. Other wells of the study area contain shale within the same sequence. The thickness of this sequence in well 15/3-1S is nearly 90 m but the thickness abruptly decreases in well 15/3-3 to 30m and finally it is absent in well 24/12-1R in the Vana sub-basin area (Figure 5.1 & 5.6).

MFS J63 is another significant MFS; its surface shows a very sharp marker for the lithological change as the gamma and sonic ray values decrease here immediately above the surface. The sequence J63 contains large sand bodies in wells 15/3-3, 15/3-7 and 15/3-1S and also in well 9/24-b4 (Figure 5.6 & 5.7).

The sand bodies thickness is nearly 130m in wells 15/3-3, 15/3-7. In well 15/3-1s the sequence carries sand layers alternately with shale layers. This sequence is not found in wells 24//12-1R, 15/3-2, 16/1-5 and 24/12-2T2 .The sequence is also found in wells 16/1-5 and 15/3-5 but these wells are mainly shale dominated. Few thin sand bodies are also found in the shale dominated well 15/3-2 within this sequence.

MFS J64 is characterized by both high gamma peak and sonic reading. Above and below this surface the gamma value sharply decreased in most of the wells. The sequence J64 also contains sand bodies in wells 15/3-3, 15/3-7 and 15/3-1S but the thickness nearly 50m of this sequence is less than the J63 sequence (Figure 5.6). The thickness of the sequence is reduced towards the northern part of the study area in the Vana sub-basin and is absent in well 24/12-1R (Figure 5.6). This sequence is not found in wells 15/3-2 and 24/12-2T2. The sequence also carries clean sand bodies in well 16/1-2.

MFS J66A shows high gamma and sonic peaks above the MFS J64. The surface is found in wells 9/24-b4, 15/3-3, 15/3-7 and 15/3-1S. Above this surface the gamma value decreased temporarily but increased again until reaching another gamma ray peak in MFS J66B. The sequence J66A has a maximum thickness in well 15/3-1S where it is more than 55m (Figure 5.6 & 5.7).

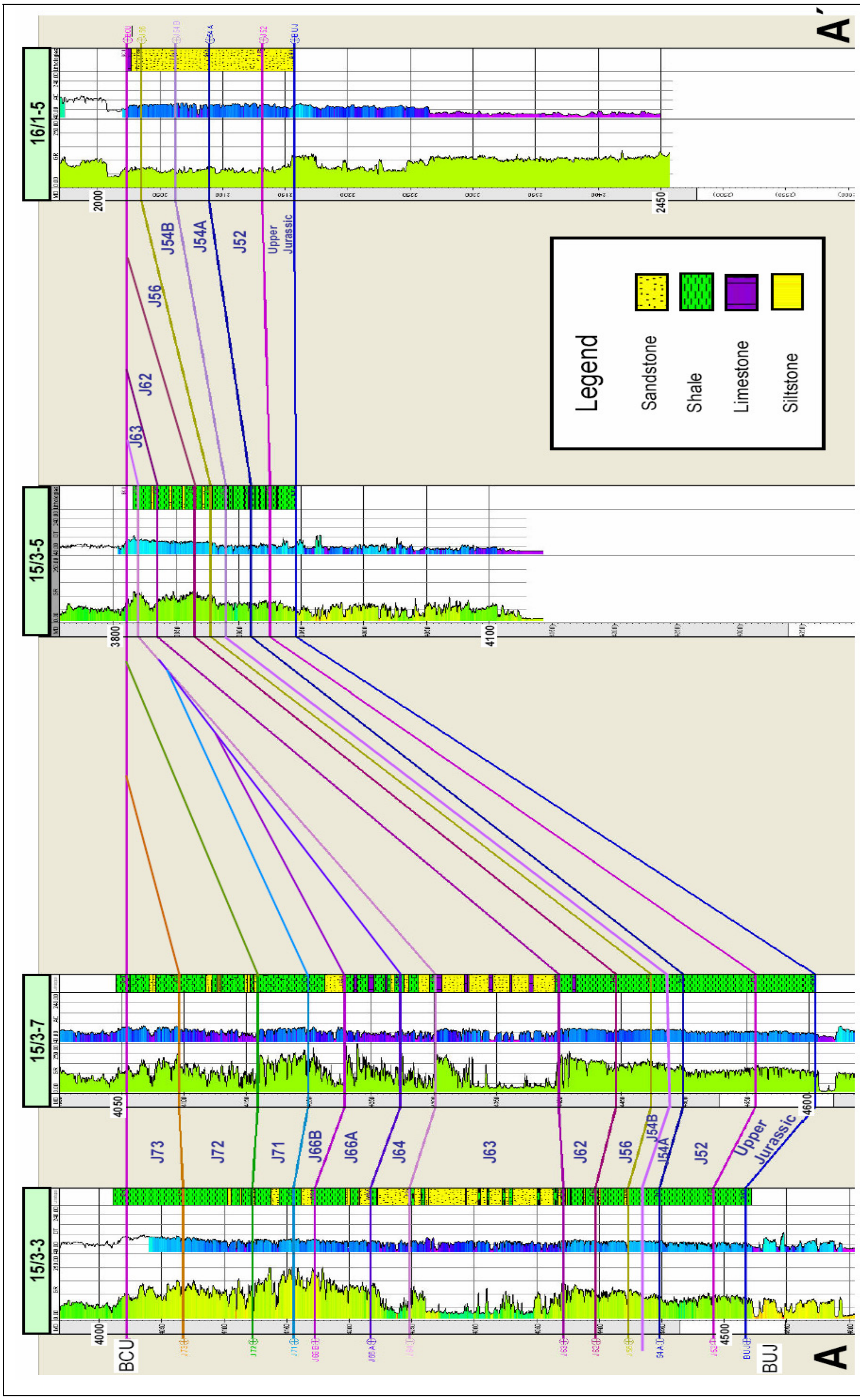

Figure 5.5 Well Correlation profile AA´ through key wells with identified J sequence and surface Base Cretaceous (BCU) flattened on top; GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

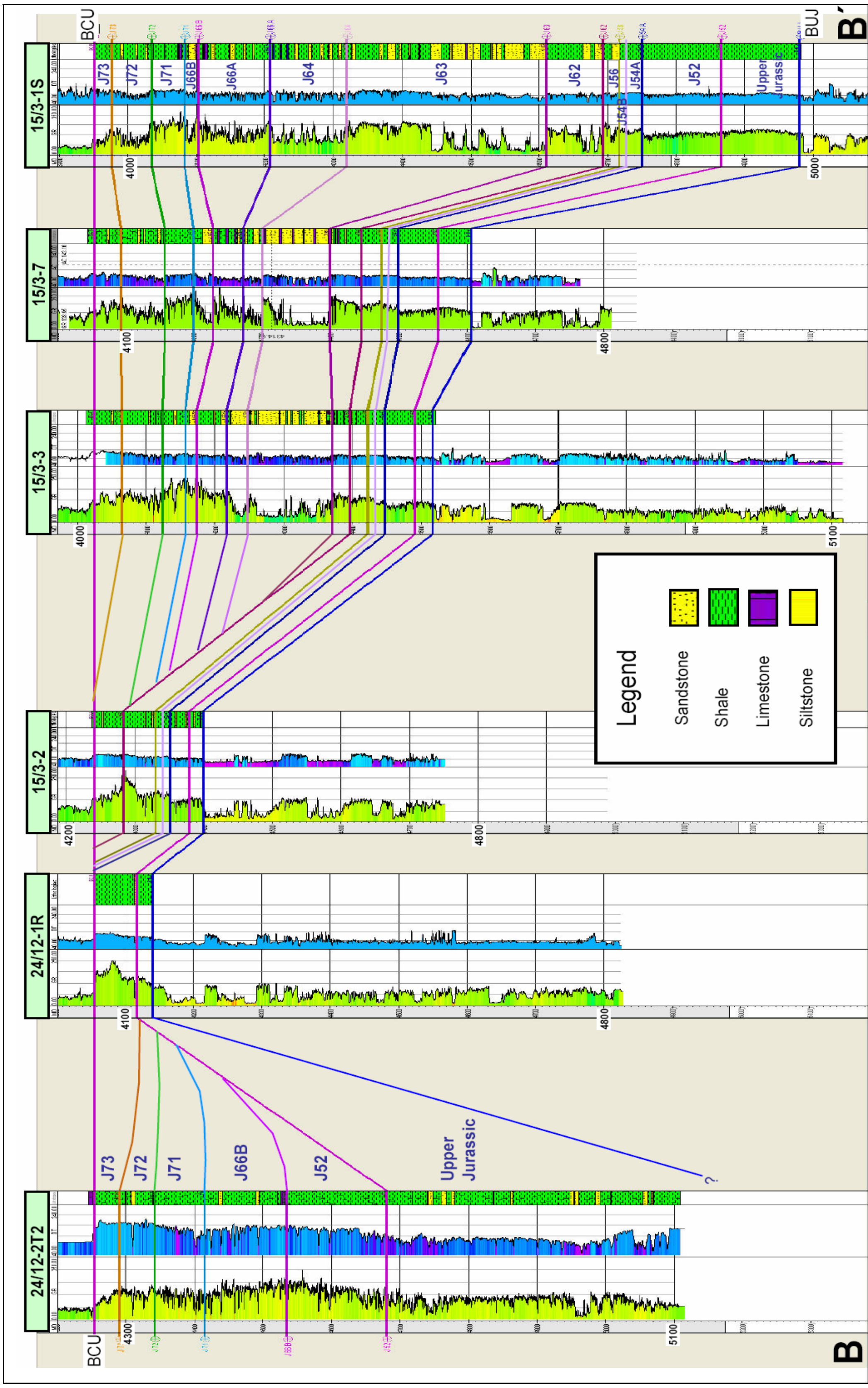

Figure 5.6 Well Correlation profile BB′ through key wells with identified J sequence and surface Base Cretaceous (BCU) flattened on top; GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

MFS J66B shows high gamma and sonic values. The sequence J66B is not found in the area near wells 15/3-5,16/1-5,15/3-2 and 24/12-1R.In the south central part of the study area near the Vilje sub basin the thickness of the sequence is 25m on an average and near well 9/24-b4 the thickness reached up to 50m.The well 24/12-2T2 shows a thick package of the J66B sequence measuring up to 120m.

In well 24/12-2T2 this sequence is developed just above the J52 sequence .This sequence jumping from J52 to J66B in the area was found on the basis of biostratigraphic correlation. The missing sequence in the area near this well indicates that the area was probably a structurally high from J52 time to J66B time.

MFS J71 is another gamma ray peak marked above the MFS J66B; it is the upper boundary of sequence J66B. The maximum thickness of the sequence J71 found in well 24/12-2T2 is approximately 80m in the Vana-sub basin and about 30 m in the Vilje sub-basin wells 15/3-3, 15/3-7 and 15/3-1S.This sequence is not present in wells 24/12-1R,16/1-2,15/3-2 and 15/3-5 (Figure 5.6 & 5.7).

MFS J72 is marked by high gamma ray peak. Sequence J72 shows gradually increasing gamma and sonic reading until it reaches another MFS J73. The overall thickness of the sequence J72 is 60 m to 70 m found in wells 9/24-b4, 15/3-3, 15/3-7 and 15/3-1S in Vana and Vilje sub basin. This J72 sequence was not found in the eastern and central part of the study area in wells 16/1-5, 16/1-2, 15/3-2, 15/3-5 and 24/12-1R.

MFS J73 is marked by high gamma ray peak found in wells 9/24-b4, 24/12-2T2, 15/3-3, 15/3-7 and 15/3-1S. MFS J73 was not found the eastern and central part of the study area in wells 16/1-5, 16/1-2, 15/3-2, 15/3-5 and 24/12-1R .Overall thickness of the J73 sequence is around 40m on an average (Figure 5.6 & 5.7) in the studied area.

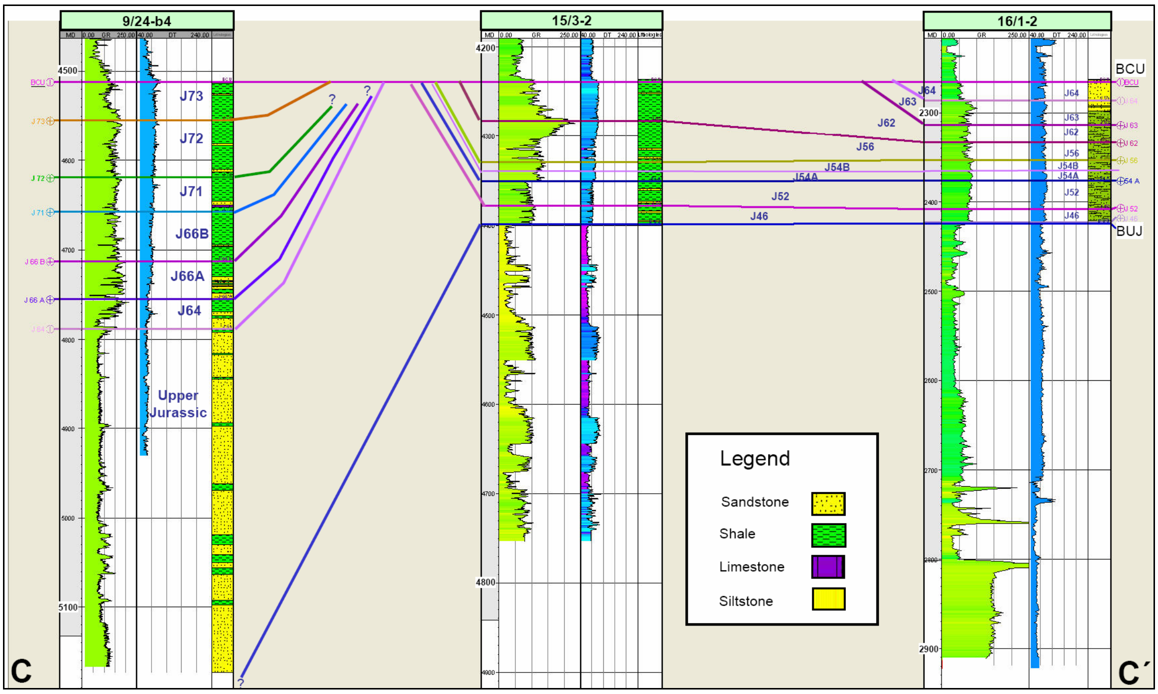

Figure 5.7 Well Correlation profile CC′ through key wells with identified J sequence and surface Base Cretaceous (BCU) flattened on top; GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

Base Cretaceous Boundary (BCU) is the upper most surface of the interpreted studied area where the gamma and sonic ray show the highest value but above this surface the gamma value abruptly decreases.

The interpretations of these surfaces (MFS J46 to MFS J73) give an overall idea about the sediment distribution of the area within the particular sequences. Three lines are chosen (Figure 5.5, 5.6, 5.7) to find out the sediment distribution from west to east and from north to south of the area. Chapter six mainly focuses on these sequences developments and a probable depositional model of the area.

6 Facies Association and Depositional Environment

Facies association and depositional environment of the studied successions are presented in this chapter and illustrated by combination of seismic, well correlation and core log interpretation. This chapter presents the recognized facies distribution together with depositional model of the study area.

6.1 Lithofacies

The sedimentary rock types that occur within the Upper Jurassic successions are highly variable. They range from conglomerates to almost entirely mudfills and were formed by the whole range of gravity-driven depositional processes: high- and low-density turbidites, debris flows, and hemi-pelagic deposition.

In the studied section, 10 wells are selected for well correlation. From them mainly three wells are selected to interpret the detailed lithofacies (mainly sand) distribution of the area. The chosen wells are 15/3-3, 16/1-5, 16/1-5a and 9/24-b4. Well 15/3-3 located in the south central part of the study area in the Vilje Sub-basin, 9/24-b4 is located in the north western part (border of East Shetland) and 16/1-5 in the south eastern part of the study area (Gudrun Terrace).

Upper Jurassic deposits of the South Viking Graben area are mainly mud/shale prone. The shale deposits also contain sand bodies that can accumulate economically variable hydrocarbons under favourable conditions. The sandstone cores are mainly selected from four wells in the studied area for detailed facies analysis. The cores are taken at depths ranging from 4308m to 4262 m in well 15/3-3, 2066m to 2023m in well 16/1-5, 2150m to 2123m in well 16/1-5A (side track of well 16/1-5) and 4979m to 4793m in well 9/24-b4 (Figure 6.1 to 6.4).

The core analysis allows direct observations of different sedimentary structures preserved on the core bodies of the studied sections. These sedimentary structures are finally classified into eleven (F1 to F11) facies providing different depositional conditions during the time of their depositions. The identified facies are F1 to F11 and their characteristics as well as possible depositional environment are represented in table 6.1.

In well 15/3-3, the selected core was taken from 4308m to 4262m depth. This well contains F2, F10 and F8 facies at the bottom of the core (Figure 6.1). The average thickness of each facies is nearly 0.25 to 1.5 m. These facies were developed in low energy turbidity condition.

F3 and F9 facies were developed above the previous facies in a high energy debris flow conditions. The thicknesses of F3 and F9 facies are nearly 3 to 5 m on an average. The topmost facies of this well are characterized by granule size particles and the overall thickness of this facies is nearly 0.1m. The fining upward F8 facies identified at a measured depth of 4300m is a very good candidate for a Bouma sequence (Figure 7.1).

In well 16/1-5 the selected core was taken from 2066m to 2023m depth and it was approximately 43m (Figure 6.2) thick, and in the 16/1-5A well the core was taken from a depth 2150m to 2123m which was only 27m thick (Figure 6.3). The selected cores contained medium to coarse grain clean sand. Sedimentary structures like Planer crossbeds and bioturbation were found in the 16/1-5 well. Most of the sedimentary structures were destroyed by intense bioturbation. The base of the core covers a 5m to 7m thick package of bioturbated structureless F6 facies.

The overlying facies F11 are massive structureless sandstone nearly 8m thick where the intensity of bioturbation is relatively low compared to the lower facies. The facies continued from 2055m to 2025m and above the facies a 1m thick cross bed facies F7 was identified. The top of the core was characterized by the development of the shore face calcite rich cemented conglomerate facies. In the side track well 16/1-5A the same type of facies were formed in well 16/1-5 but in some places it showed faint trough cross beds nearly 0.1 meter thick developed individually which could be the result of a higher energy condition deposit.

Table 6.1 Lithofacies description and interpretation based on cored intervals in wells

Lithofacies	Description	Interpretation
Facies F1	This facies consist of intercalated gravely to pebbly sandstones, Occasionally cemented. The thickness of the facies is around 1.0-1.5 meter.	The facies was developed by sandy debris flow. (Cullen, Ward and Warrander, 1997). The energy condition was high during the time of deposition.
Facies F2	Heterolithic interbedded fine laminated sandstones and mudstones developed climbing current ripple.	Deposition from low density mature turbidity current. The presence of climbing ripple indicates the rapid deposition from a constant sediment supply (Cullen, Ward and Warrander, 1997).
Facies F3	Nearly 1.0-3.5 meter thick. Thick sand bodies contained mudclast arrange randomly without any specific arrangement. Occasionally developed shale rip-up clast at the top.	Deposition from high energy debris flow. The presence of shale rip up clast indicates the top most part of a single flow.
Facies F4	Trough cross bedded sandstone developed in fine to medium grain sandstone. Beds were weakly developed around 0.1m thick	Presence of trough cross bed indicates the deposition during high energy storm weather condition. (Reading, 1996).
Facies F5	Medium grain, incline bedded, well sorted sandstone.	Deposition from grain flow generally develops in the steep slope. This grain flow develops from intergranular collisions that create dispersive pressure because of shearing (Bagnold, 1954).
Facies F6	Medium to coarse grain bioturbated sandstones, facies are 3 to 12 meter thick .Occasionally calcite cemented, glauconites in some places.	Deposition during high energy fair to storm weather condition in Shoreface area.
Facies F7	Fine to medium grain cross bedded sandstone.	Presence of planer cross bed indicates the deposition under fair weather condition (Reading, 1996).
Facies F8	Fining upward facies 0.25 m thick. Gravel to coarse grain sandstones found at the base; ripple lamination in the middle and finally thin shale layer developed at the top of the facies (candidate Bouma sequence).	Deposition from mature turbidity currents with late stage traction-plus-fallout sedimentation and later suspension fallout (Cullen, Ward and Warrander, 1997).
Facies F9	Massive sandstone beds fine to medium grain, moderately sorted.	Deposited mainly by the sandy debris/grain flow (Reading, 1996).
Facies F10	Gray to dark black shale with silt streaks.	Formed by very low density muddy turbidity currents, deposited by the suspension fallout (Cullen, Ward and Warrander, 1997).
Facies F11	Bioturbated massive sand bodies with abundant granules at the base or within the whole sand bodies.	Deposition under high energy shore faces condition.

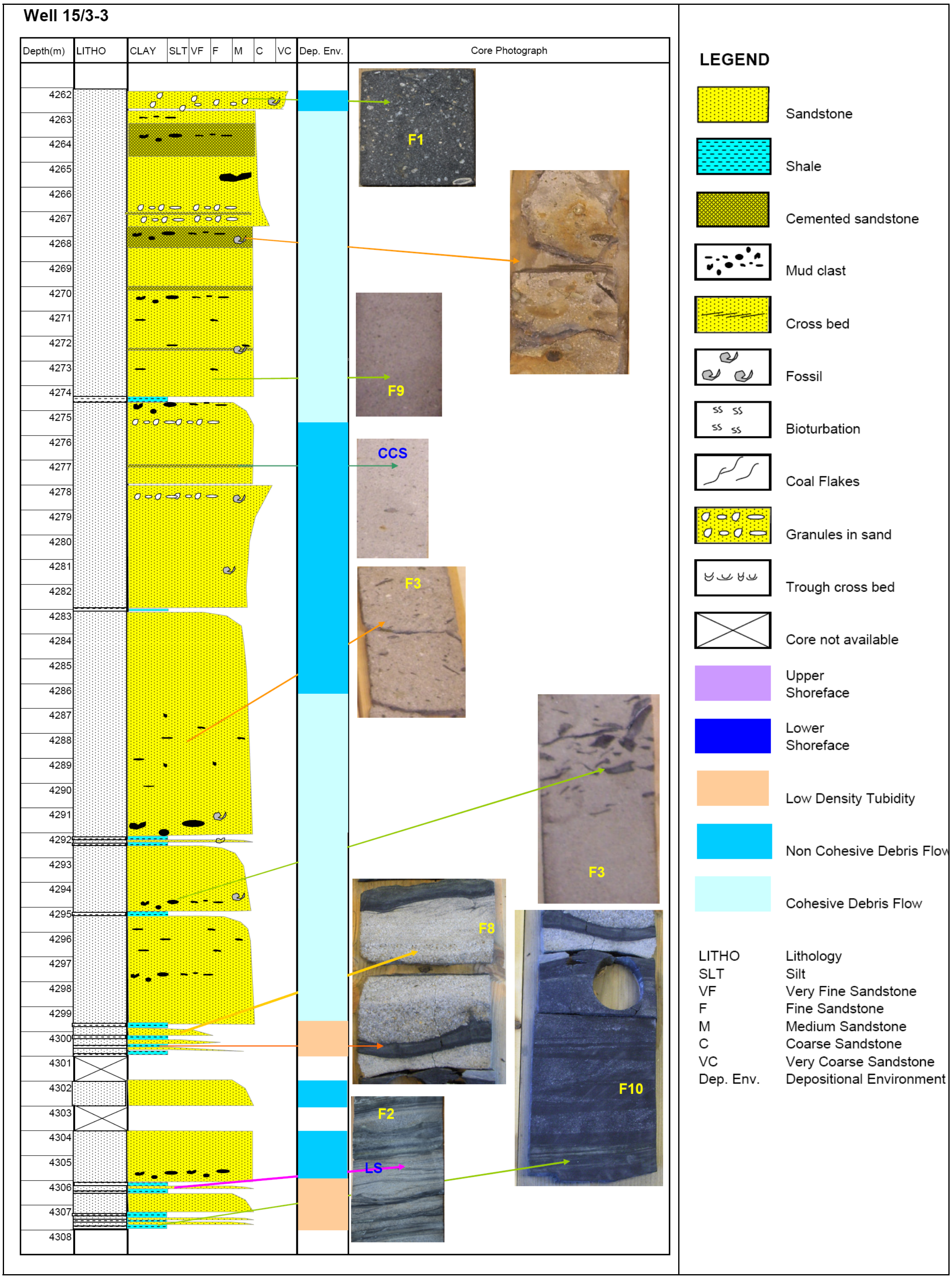

Figure 6.1 Cored section of well 15/3-3 and facies codes, See Table 6.1 for details in lithofacies. Description and core photographs of facies and facies association with possible depositional environment, CCS=Calcite Cemented Sandstone, LS=Laminated Sandstone.

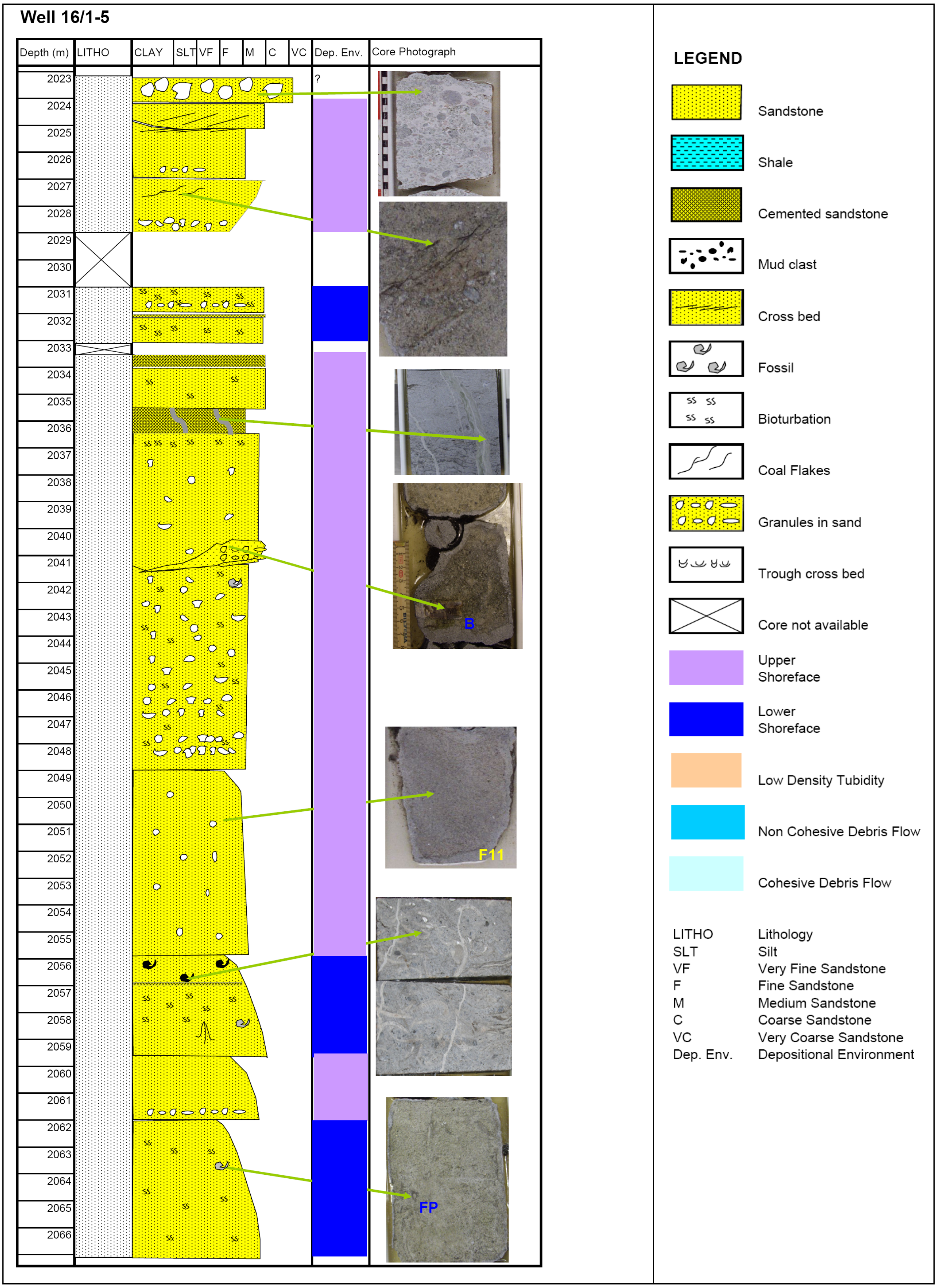

Figure 6.2 Cored section of well 16/1-5 and facies codes, See Table 6.1 for details in lithofacies. Description and core photographs of facies and facies association with possible depositional environment, B=Belemnite, FP=Paleophycus Fossil.

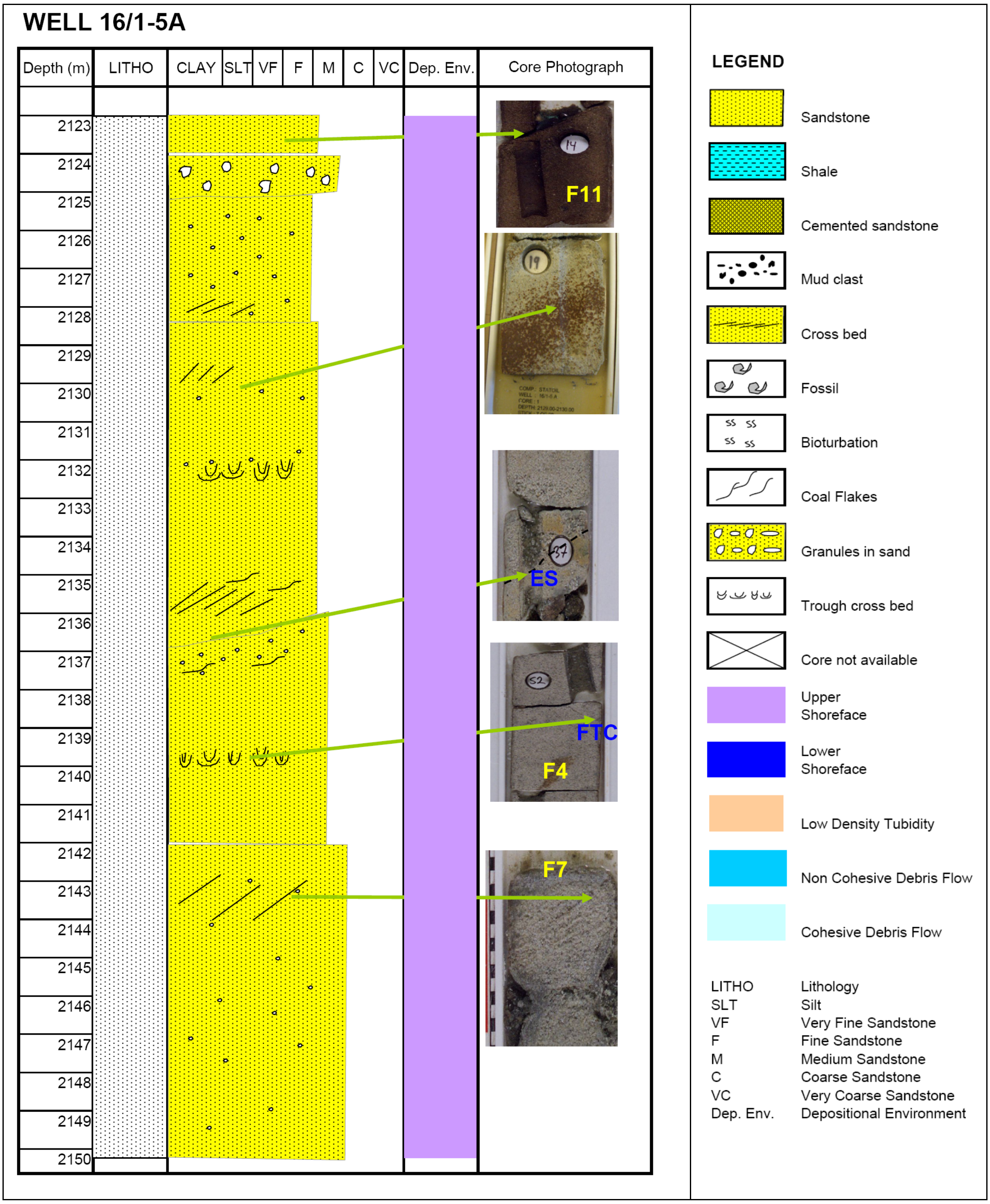

Figure 6.3 Cored section of well 16/1-5A and facies codes, See Table 6.1 for details in lithofacies. Description and core photographs of facies and facies association with possible depositional environment, ES=Erosional Surface, FTS=Faint Trough Cross Bedding.

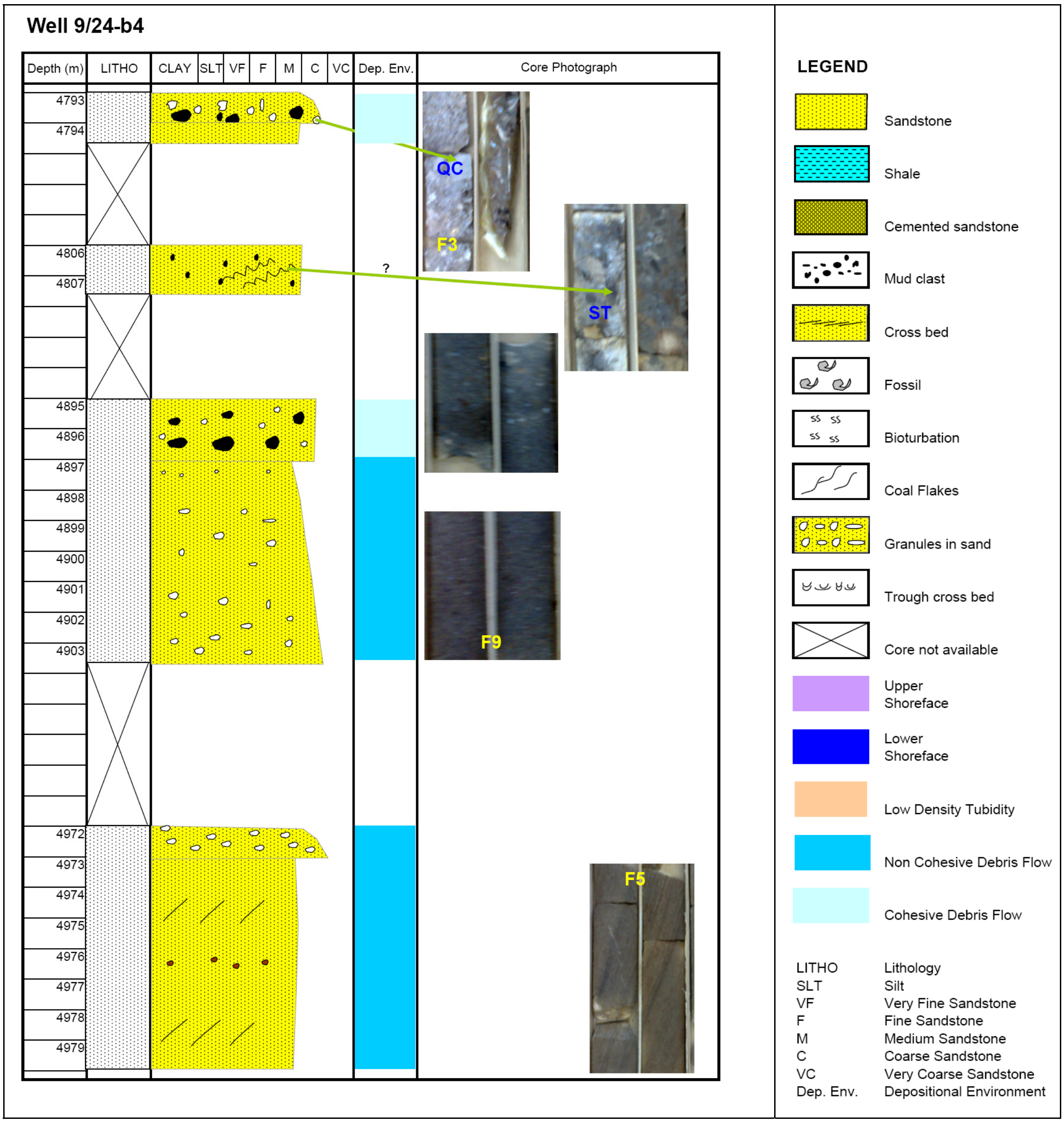

Figure 6.4 Cored section of well 9/24-B4 and facies codes, See Table 6.1 for details in lithofacies. Description and core photographs of facies and facies association with possible depositional environment, QC=Quatz Clast, ST=Stylolite.

In well 9/24-b4, the core was taken from 4979m to 4793m depth .Most of the cores were missing in this well. So the total core thickness found for facies analysis was 21m only. It shows that the area near well 9/24-b4 contain the types of facies found in well 15/3-3 but the size of the mudclast and other coarse grain facies found in the well comparatively coarser than it in well 15/3-3.It signifies that the energy condition during the deposition of the sediments near well 9/24-b4 was higher than the sediments deposits near well 15/3-3. F5 Facies (massive sand body) found in the lower part of the core of this well (Figure 6.4) is around 7m thick. The massive poorly sorted sand body represents F9 facies found in the middle part of the core and finally F3 facies found at the top most part of the core. As most of the core cuttings are not found in this well, the exact thickness of the facies could not be determined in this well for these two (F9 and F3) facies types.

6.2 Facies Association

From the above facies observations, different types of sedimentary facies can be put to in specific groups where the group will indicate a particular type of depositional environment known as Facies association. From the lithofacies analysis, three types of facies associations have been identified in the studied successions, i.e. Marine mud, Shoreface and Deep marine sand facies associations. These are described and interpreted below. Based on the interpretation of the facies associations and their internal relationships, the facies associations are grouped to represent depositional environments.

6.2.1 Marine mud/shale

Description: this facies association consists of light grey to grey colour shale, sometimes also black to dark brown occasionally micaceous, pyritic, non calcareous to calcareous, laminated with some silt and sand stringers (Figure 6.1).

Interpretation: fine grain shale was deposited (probably by the suspension process) in the distal shelf, slope and deep marine fan environments. The energy during the time of deposition was low probably because it was deposited during fair weather condition especially where the sediment is finely laminated (Walker and Plint, 1992). Dark grey to black shale deposits indicate pelagic deposits in the dysaerobic zone (Hunt, 1996).

6.2.2 Shoreface Sandstone

Description: This deposit consists of fine to coarse grain, medium to poorly sorted sandstone and siltstone. From core analysis this facies association is characterized by light grey to bluish grey, fine to very coarse grained sandstone with some granules (dominantly quartz) ,angular to sub angular in size and highly bioturbated (F6) in some places. Calcite, dolomite cementations are also found in some places (Figure 6.1). Typical sedimentological structures are planer (F7) and trough cross bedding (F4). Presences of coal flakes are also common in the area. Abundance of granules (F11) cuttings could be the result of erosional surfaces formed during storms energy condition. Presence of fossils like Belemnites and Paleophycus are also common in the studied section (Figure 6.2).

Interpretation: The different Sedimentary structures and presences of clean sand bodies in the area is because of the wave action under fair and storm weather conditions. In a shoreface environment, storm weather condition transported sand grade sediments towards the land and fair weather condition removed the silt and clay type particle by the winnowing effect (Hunt, 1996) developing sand bodies in shoreface environment. Vertical changes of the sedimentary structures indicate the change of energy condition of the sediments flow caused by the action of different fair and storm weather environment restricted within upper to lower shoreface deposits.

The presence of characteristic fossils (mentioned above) of the area also established the deposition of the shoreface environment. Highly bioturbated zones normally indicate lower shoreface deposit as the wave action is comparatively low. Presence of cross beds and less bioturbation indicate upper shoreface deposits where the wave and tide action was high.

Coal flakes are also present in few places in well 16/1-5 (Figure 6.2) indicating that the area was not far from land. The thickness of cross beds is not more than 10 to 20 cm and in some places it is hard to identify. The above information indicates that the deposition was a shore face deposit.

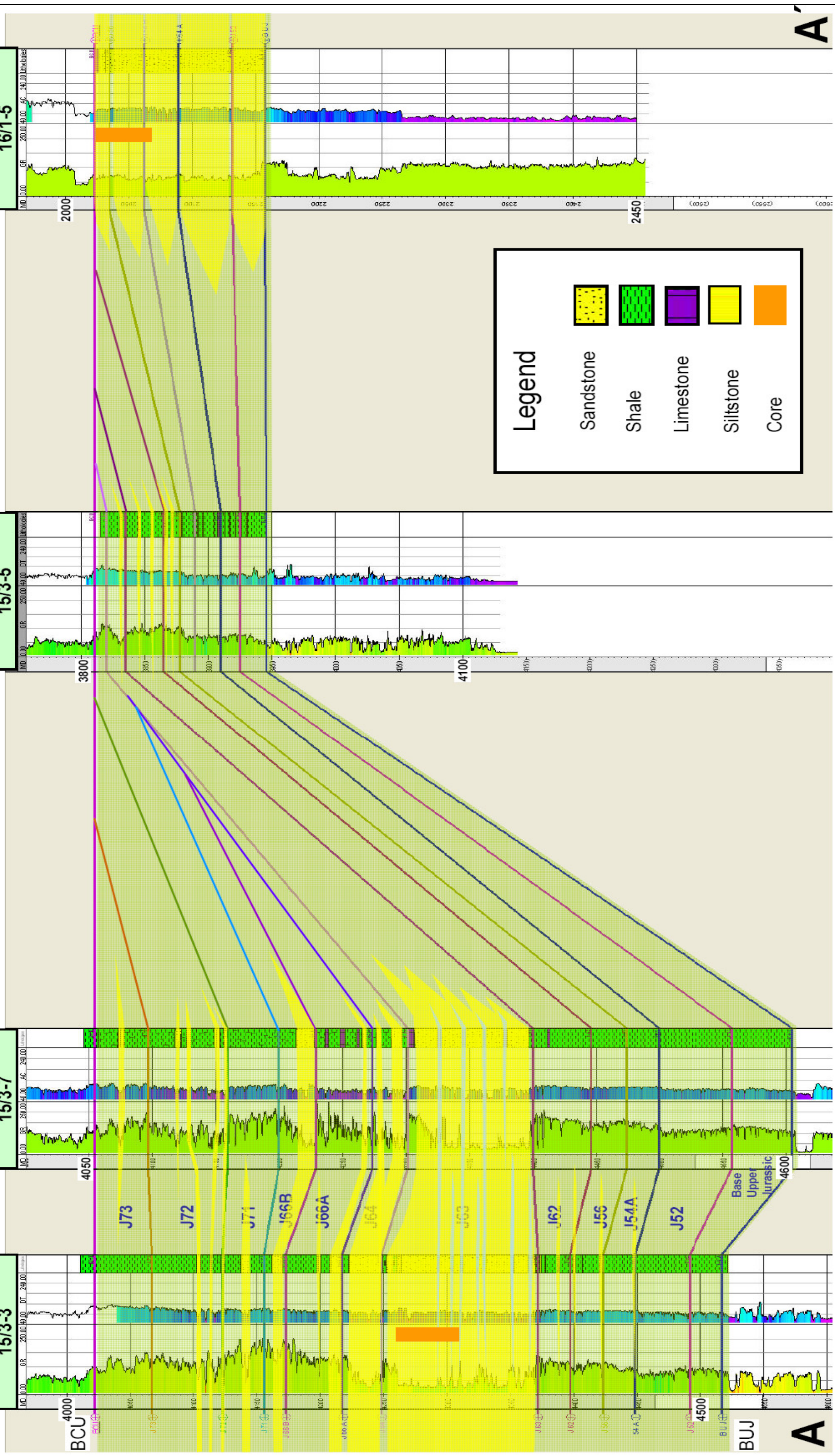

Figure 6.5 Simplified facies and sequence stratigraphic correlation showing the distribution of sand reservoir in profile AA´ through key wells of Upper Jurassic interval (J52 – J73) flattened on top Base Cretaceous (BCU); GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

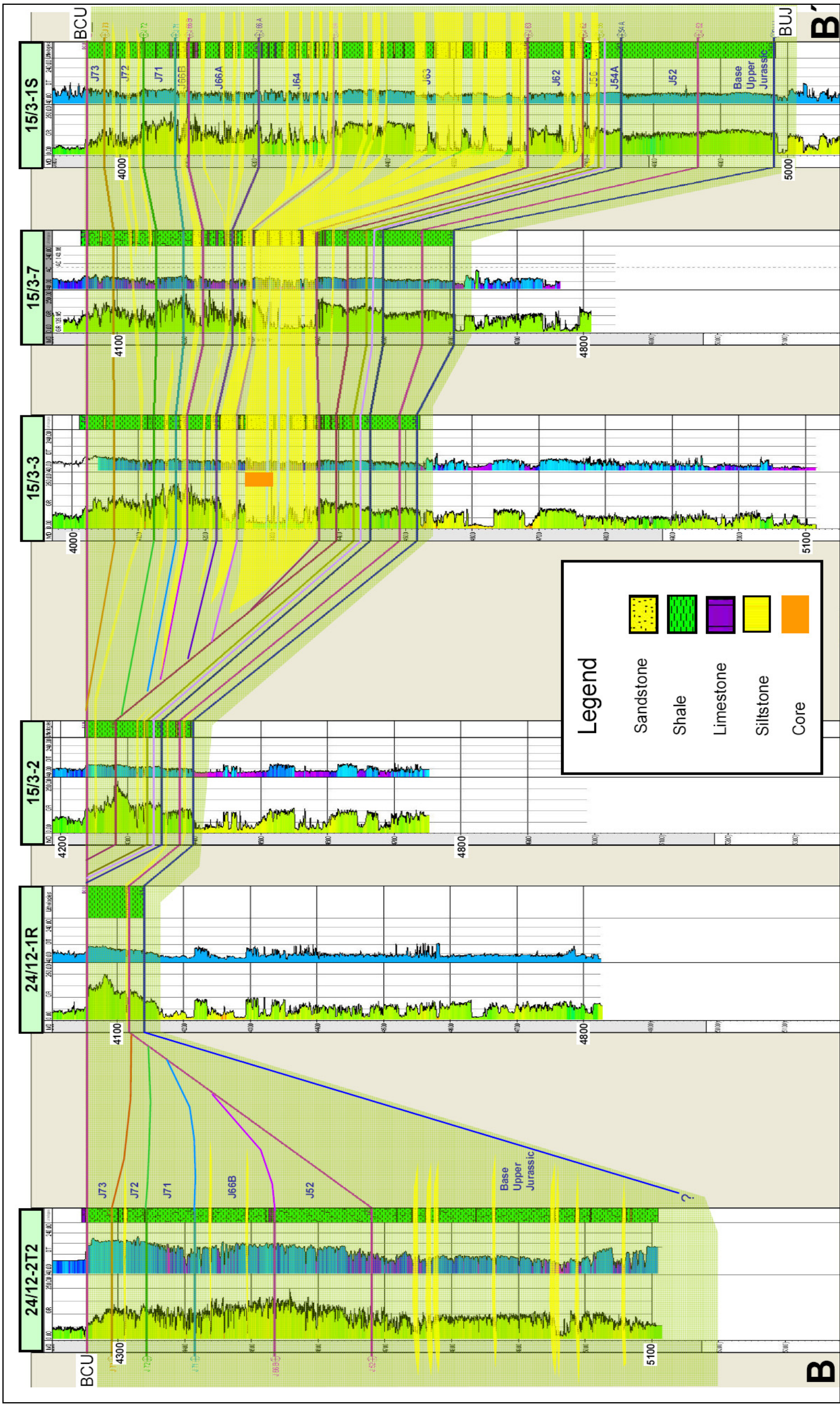

Figure 6.6 Simplified facies and sequence stratigraphic correlation showing the distribution of sand reservoir in profile BB´ through key wells with identified J sequence and surface Base Cretaceous (BCU) flattened on top; GR = Gamma Ray, DT = Sonic Log. The vertical axis in meters below the rig floor.

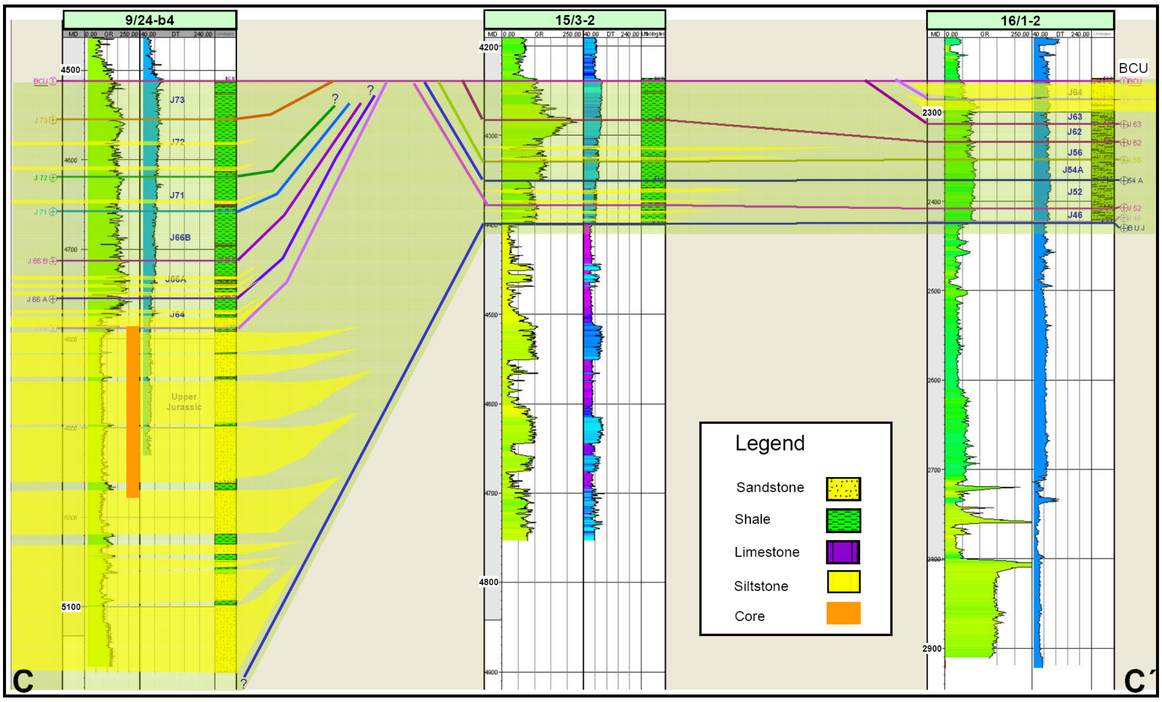

Figure 6.7 Simplified facies and sequence stratigraphic correlation showing the distribution of sand reservoir on profile CC´ through key wells with identified J sequence and surface Base Cretaceous (BCU) flattened on top; GR = Gamma Ray, DT = Sonic Log. The vertical axis is in meters below the rig floor.

6.2.3 Deep marine sandstone

Description: This facies association range in grain size from fine to coarse grain sandstones. It contains massive beds (F5), sand bodies with scattered mudclast and shale rip-up clast at the top (F3),scattered pebbles and granules in sand (F1),alternation of laminated sand and mud/shale (F2),shale with sand and silt streaks (F10) and markable Bouma sequences (F8) (Figure 6.1).

Interpretation: Presence of shale rip-up clast in the sand bodies indicate that the top most part of a single flow was developed as a low energy debris flow and the scattered mud clast in sand indicats either a debris flow or a high energy turbidity flow in the study area. Presence of sand bodies without any shale layers is the evidence of grain flow deposit. Shale dominated study area was also developed by low density muddy turbidity currents. In few places the turbidity flows were matured enough to develop Bouma sequences (Martin, 1992, and Reading, 1996). All of these facies are very common in the proximal canyon or channel or even in the slope fans or basin floor fans areas (Stow, Howell and Nelson, 1985).

6.3 Depositional Environment

The reconstruction of depositional environment is the targeted outcome of this thesis. It is the combined result of well correlation, biostratigraphic information, seismic interpretation and lithofacies identification. The wireline-log response trends notify the different maximum flooding surfaces in the selected wells and biostratigraphic data signify the presence of different Upper Jurassic genetic stratigraphic J sequences boundary in depths. Seismic interpretation provides the reliability of the interpreted sequences and maximum flooding surfaces and their lateral extension in the whole study area.

6.3.1 Sedimentation history of the Facies Development

From facies interpretations of cores analysis in the studied area, it is clear that the Upper Jurassic deposits were mainly shale dominated with few sand bodies within it. The depositional conditions during the time of facies developments (F1 to F11) have been discussed above. Here attempts have been taken to summarize all facies characteristics to draw facies maps of the study area.

It is already mentioned that there are mainly three types of facies associations identified in the study area. The three profiles (Figure 6.5, 6.6 & 6.7) are selected to see the facies distributions along with the profiles of the area. The horizontal facies distribution maps (Figure 6.8, 6.9) have been drawn taking help from those three profiles and seismic interpretation results of the study area.

To understand the sand bodies' distributions, depositions and stratal geometries, more realistic depositional models have been constructed to understand the geological conditions during the depositions of the sand bodies within the shale dominated sedimentary sequences in the study area. To construct the sedimentological models of the entire study area, the following observations have been taken into considerations:

1) Huge bioturbated sand deposits are found in the well 16/1-5 near the eastern margin of the area.

2) The selected profiles AA`, BB` and CC` show that most of the maximum flooding surfaces are onlapping, which were the results of transgressions.

3) The fossils content, lithology and sedimentary structures prove that the depositions took place under marine conditions from shallow marine shore face (marginal part) to deep marine debries flows and turbidites (central part of the study area) deposits.
4) The selected sand bodies developed a boxcar to fining up trend in the study area with some transgressive shale bodies within it.
5) Presence of glauconites ,Planar cross beds and trough cross beds in the wells near the eastern part of the study area indicate shallow marine shelf to shore face deposits (well 16/1-5 and 16/1-5A)

The distributions of different facies developing in the study area have been presented by the vertical depositional model along the selected profile AA`, BB` and CC` (Figure 6.5, 6.6 & 6.7).

6.3.2 Sedimentation history of the Sequences Development

The sedimentation history of the Upper Jurassic J sequences in the study area can be summarized as follows:

Sequences J 46 to J 52

The study area (Figure 6.8 A) was a marine shale deposit with few sand stringers in it. The shore face deposit was developed in the south eastern part at the same time of the study area. The eastern boundary was probably structurally high or emergent area during the development of those sequences.

Sequences J52 to J56

Depending on sediment types and fossil content of the different selected wells, it can be concluded that the area went under erosion or there was no deposition near wells 24/12-1R and 24/12-2T2 during the deposition of J52 to J56 sequences (Figure 6.8 B). So the area was probably uplifted by tectonic movement. Rest of the study area was covered by marine shale deposits indicating low energy marine environment.

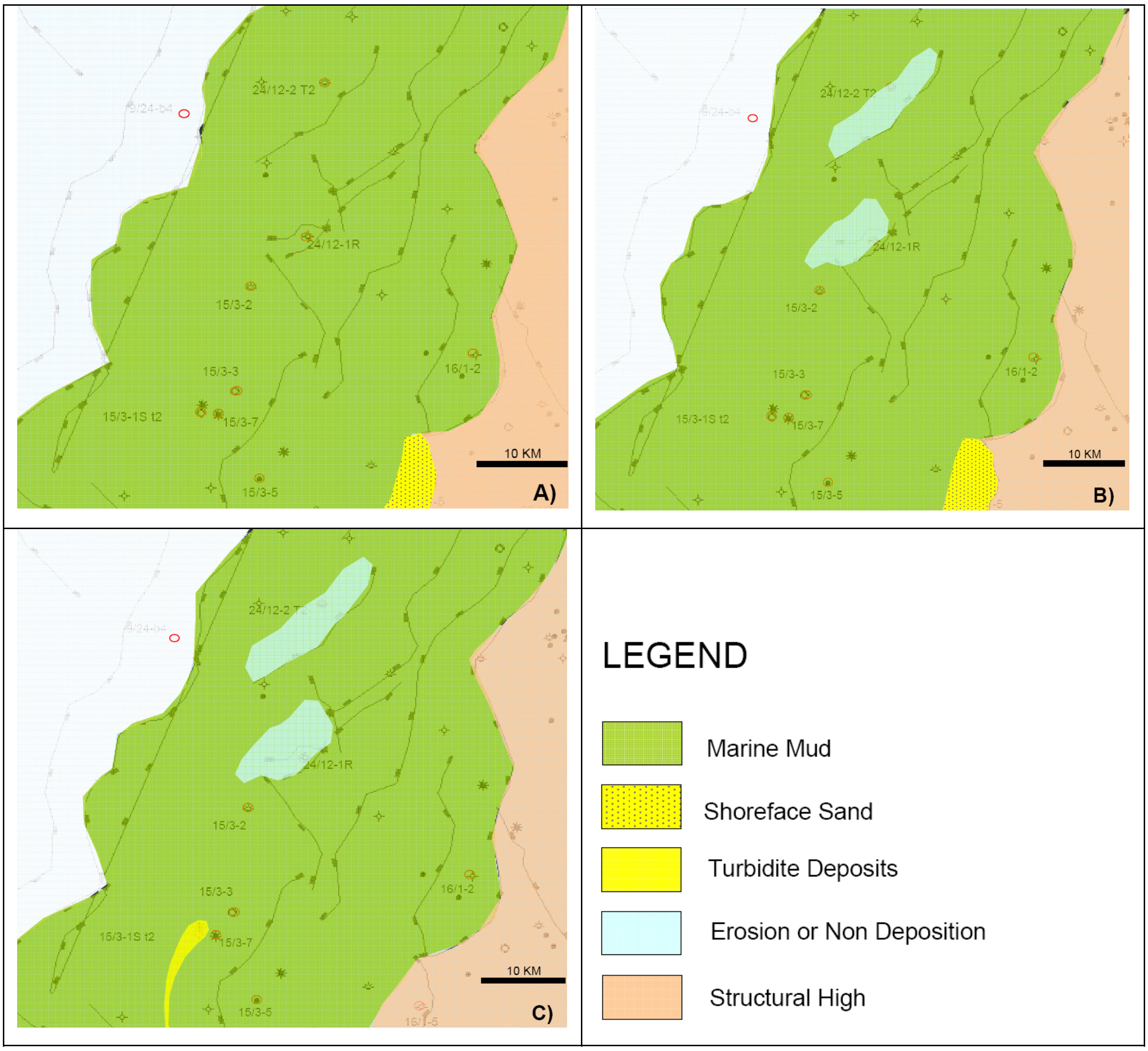

Figure 6.8 Palaeogeographic maps of Oxfordian to Late Kimmeridgian interval, showing the shoreface to deep marine deposits. Sequence intervals are A) J46-J52, B) J52-J56 and C) J56-J62

Sequences J56 to J62

Based on well correlation it can be said there were markable sandstones deposits in the well 15/3-1S, (Figure 5.6) which thinned towards the wells 15/3-7 and 15/3-3 and that the thickness of the sand bodies gradually decreased towards the north. Rest of the area was covered by shale dominated marine deposits. The areas near well 24/12-1R and 24/12-2T2 were still uplifted .Sand developed near well 15/3-1S was probably transported from the southern part of the study area. The previous shore face deposit near the well 16/1-5 was also subjected to erosion during the time of development of these sequences (Figure 6.8 C).

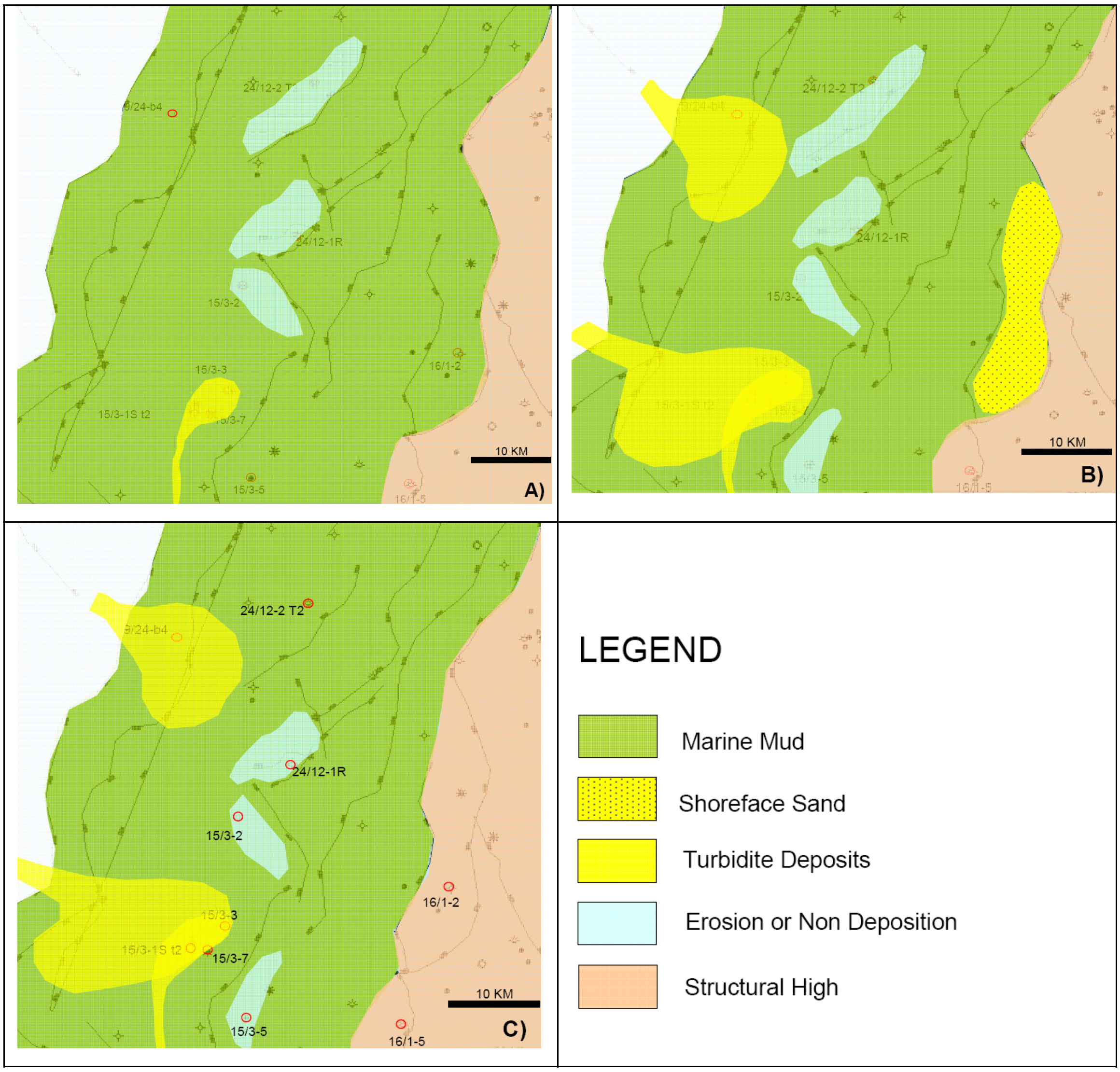

Figure 6.9 Palaeogeographic maps of Volgian to Late Ryazanian interval, showing the shoreface to deep marine deposits. Sequence intervals are A) J62-J63, B) J63-J66A and C) J64-Base Cretaceous

Sequences J62 to J63

During the development of the J62 and J63 sequences, uplift continued from the north towards the south in the central part of the study area, a feature which becomes clearer after sequence J63. The sand flows increased near the wells 15/3-3, 15/3-7 and 15/3-1S which can be understood by viewing the well correlations and seismic distribution of the sand bodies within the sequence. This sand was transported probably by gravity (turbidities and debris flows) from the south developing small sub marine fans/channels in the Vilje Sub-basin (Figure 6.9A).

Sequences J63 to J66a

Developments of these sequences are important from a petroleum geological point of view in the North Sea as they could accumulate hydrocarbon. The selected sequences show that the erosional activity continued also near the well 15/3-5 developing Shore face deposit at the eastern margin of the studied area. The maximum flooding surfaces developed during this time can be easily recognized by the onlapping features seen in the seismic interpretation profiles (Figure 4.4). The sediments transported from the East Shetland platform developed a sub-marine fan in the low lying basin area (Figure 6.9B).

Sequences J66A to Base Cretaceous (BC)

During the development of these sequences, the rate of subsidence of the basin increased more than the rate of depositions within the basin. So most of the study area began to be inundated and became shale prone (Figure 6.9C). Thin sand beds within the shale layers also developed in the distal part of the study area was an outcome of probably the turbidity flow deposits.

7 Discussion

7.1 Sequence Stacking Pattern

The sequence stratigraphy approach is used to interpret sediments deposited in an extensional graben system. It allows the assessment of the development of genetically related deposition system. This provides a framework for the prediction of reservoir rock development. The sequence depositional environment is controlled by a variety of effects such as tectonic control, sea level fluctuation and sedimentation rate (Surlyk, 1989).

The individual sequences of the Upper Jurassic deposits in the study area are recognized by the responses of gamma and sonic logs, biostratigraphic information and seismic sequences interpretation of the sediments. All the sequences were deposited during the active rifting in the North Sea developing the genetically related stratigraphic sequences.

In the study area, sequences J46 to J62 developed in the eastern part (Gudrun Terrace) of the area are closely spaced. Those sequences are sparsely distributed in the middle part of the area near the Vilje Sub basin which gradually ends up in the western part of the study area near well 9/24-b4. But the sequences from J63 to the Base Cretaceous boundary are developed in the entire study area and the thickness is increased near to well 9/24-b4. So during the time of these (J63 to J73) sequences development, tectonic movement caused the sea level to rise and an active subsidence in the Vilje Sub basin.

The tectonic activity also elevated the areas near the wells 24/12-2T2 and 15/3-2. Consequently the sediments of these areas were eroded. These sediments could be the additional sources for the deposition of the latter sequences development in the surrounding basin areas. Sequence stacking finally reflects that the maximum subsidence was dynamic in the Vilje sub basin and in the north western part of the study area.

In sequence correlation, the most significant potential pitfall lies in wireline-log interpreting 3D geometry from 1D log data. As it is described in maximum flooding surfaces and as sand bodies can have similar wireline characteristics, quite different 3D geometries and trends noticed. The classic fining and thinning-upward, log patterns do not always correspond to the long-held interpretation. An equally significant pitfall relates to the biostratigraphic data with biozonation scheme showing some marker fossils which were be evidences of a long range of existence but found in more than one sequence surface marker. These pitfalls are attempted to minimize by integration with other data sets (cores, seismic data, and borehole-informations). In this study only the transgressive sequences were emphasized but it could have been possible to consider also the regressive phases within the Late Jurassic.

7.2 Controlling factors

The primary issues in sequence stacking pattern include consideration of the interaction between sediment supply and changes in accommodation space within basin. A number of factors interact in controlling depositional environments, such as climate, relief of the drainage basin, water discharge, tide and wave actions, tectonics and basin geometry (Emery and Myers, 1996, Coe, et al., 2003). However the effects can be summarized in existing accommodation space and sediment supply.

Geometry of sedimentary successions is the result of variation in rates of accumulation of sediments, eustasy, and tectonic movements (Kendall and Lerche, 1988). Development and geometry of marine strata are largely dependent on sediment supply and sea level changes whereas continental deposition take acts to a much broader spectrum of processes, both autocyclic and allocyclic. Marine sedimentary systems are to a high degree the product of sea level and climate changes since climate controls sediment supply (Galloway, 1989; Shanley and McCabe, 1994). Accommodation space available for potential deposition is created by eustasy, tectonics, and autocyclic processes. Autocyclic processes incorporate variations within the depositional system, such as compaction and subsidence by isostatic adjustment.

7.3 Seismic Relevance

The sediment pulses were most likely to be confined by the initial sea-floor topography, evident in both dip and strike views of the seismic data (Figures 4.3, 4.4). The accommodation space on the uppermost terrace was filled by shoreface complexes but the half grabens were filled by deep water turbidite deposits.

Figure 4.4 (chapter 4) represents the sequences J64, J63, J62 and J56 containing thick sand bodies in wells 15/3-3, 15/3-7 and 15//3-1S. But in well 24/12-2T2 in the same section, these sequences are absent. It may perhaps represent that the study area near well 24/12-2T2 was tectonically uplifted during the sequence development. In the study section AA′ (Figure 4.3) also reveal the sand bodies were interpreted as continued in the western part, but it would have been more definite if it were possible to interpret the sand bodies with more available corresponding wells information.

7.4 Facies Development

In the study area eleven types of facies are identified (Table 6.1) are grouped into three types of facies associations. The facies associations are shore face, marine mud and marine sand bodies. The different facies identified in the study area confirmed that the Upper Jurassic sediments consist of mainly shallow marine and deep marine deposits.

As far as shoreface deposits are concerned, it was not possible to distinguish between the upper and lower shoreface deposits of the facies associations as most of the sediments structures were destroyed by bioturbation. The sedimentary structures also were so faint in some places that it was hard to classify these sand bodies in more detail.

In well 15/3-3, the facies F8 is marked by <1m thick fining-upward intervals consisting of massive sandstone to mudstones. The detailed micro scale facies analysis reveals the complete divisions of each individual cycle. Figure 7.1 shows a comparison between the identified fining–upward cycle and classical Bouma sequence in the studied core section.

Bouma (1962) defined the sequence as the product of continuous deposition from turbidity current fundamentally consisting of sand/mud deposit. A complete Bouma sequence consists of a grain-size fining-upward succession of (a) massive or normally size-graded, sandy Bouma Ta division; (b) parallel laminated, sandy Bouma Tb division; (c) ripple/climbing-ripple laminated/convoluted, sandy Bouma Tc division;

Figure 7.1 A) Classical Bouma sequence with sediment grain size, structures, divisions of a complete Bouma Ta to Bouma Te, and sediment transport mechanisms (Weimer and Slatt, 2007). B) Cored section of well 15/3-3 at 4300 md C) Interpreted litofacies correlated with classical Bouma divisions.

(d) parallel laminated to massive, silty Bouma Td division; and (e) silt-clay, often microfaunal-rich Bouma Te division (Figure 7.1). The facies F8 characterized by the presences of Ta, Tb, Tc and Te are found in well 15/3-3 at 4300 md.

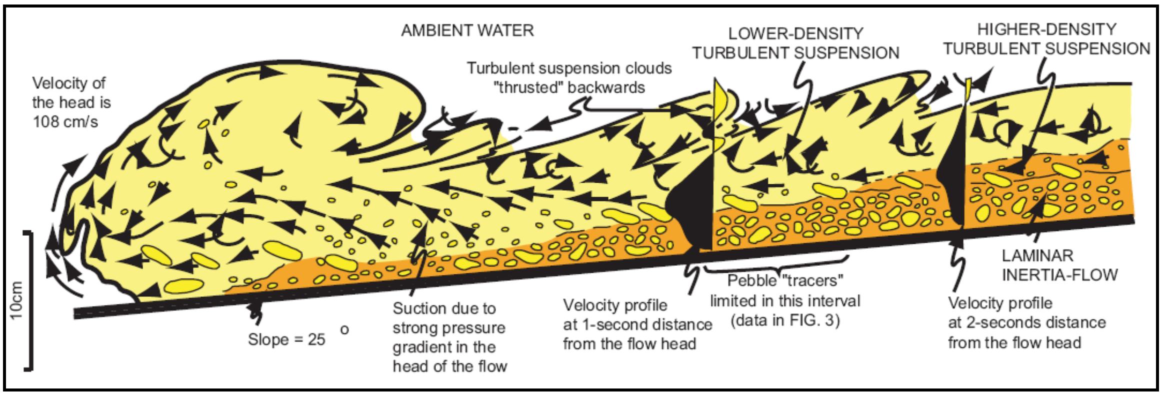

Figure 7.2 Schematic cross section shows high and lower density turbidity current with arrows point to the flow directions. Vertical flow velocity profiles are shown in shaded black. The flow is size-graded, with coarsest grains at the base of the bed. The head of this flow is thicker than the body (Weimer and Slatt, 2007).

A turbidity current is a sediment gravity flow with fluidal (i.e., Newtonian) rheology in which sediment is held in suspension by fluid turbulence (Figure 7.2). Turbidity current contains a head, body, and tail. The head may erode the sea floor and entrain sediment back into the body (Kneller and Buckee, 2000).

7.5 Style of depositional environment effected by the change of sea level

From the interpretation of the seismic sections AA´, BB´ and CC´ (Figure 4.3, 4.4 and 4.5), it can be safely asserted that sand bodies were deposited mainly in two places where they could accumulate hydrocarbon. But Upper Jurassic interpreted time structure (Figure 4.1) map shows that there were many places in the deeper areas where sand bodies could be preserved**.**

Due to lack of information, it was not possible to chart the exact distribution of sand bodies in all parts of the basin with confidence other than in two areas. Cores information illustrates shoreface sand bodies deposits in the eastern boundary of the study section. But in seismic section, these sand bodies were not possible to map as the seismic resolution of the area was very poor.

The Upper Jurassic deposits in the south Viking graben study area shows a series of sea level rise events representing the aggradational pulse of the sequences. The sea level rising is the result of both rifting and eustatic sea level changes. In the rifted area, half graben structures were developed creating accommodation space for the sediment deposition. The sediments accumulated both in the deep marine and the shoreface environments depending on the tectonic phase and the shelf topography. Tectonic movement initiated turbidite flows in the basin area. Turbidites brought sand into the deep marine environment and basin floor fans or slope fans. Thirteen late Jurassic genetic stratigraphic sequences were found in the study area.

Presence of thin sand beds in most of the shale dominated sequences in the study area could be the rejuvenation of the sediment source probably from the East Shetland platform and possibly from the Utsira High area (the last possibility is unlikely based on the result of this study).These sand bodies were deposited during different times but depositional conditions were the same.

It is already mentioned that the deep marine sands were deposited in the study area by debris and turbidity flows. But the shoreface sands were deposited by the wave and tide actions. As the transgression continued, it reduced the sediment supply above the old shoreface sand deposits and developed condensed section/shale layer. Here sand bodies acted as a reservoir rock whereas overlying shale/condensed section could act as a seal. Such types of conditions were found in wells 16/1-5 and 16/1-2 showing the presence of hydrocarbon which has not been accumulated economically (NPD 2008).

The shoreface condition was developed along the marginal eastern part of the study area which was understood by its common shoreface sedimentary structures like cross bedding, bioturbation etc. Identified fossils from the selected cores like Belemnites and palaeophycus were also indicative of the deposition under moderate to high energy well – oxygenated conditions (Howell, Flint and Hunt, 1996).

7.5.1 Sediment Partitioning

In this study the sediment distributions area shown by the sequence packages where each of the sequence has been termed as genetic stratigraphic sequence. Maximum flooding surface is the starting point of the interpretation when the sea moved towards the land and it creating more accommodation spaces for the sediment deposition during the time.

The identified sand bodies in the study area were deposited both in the deep marine and shallow marine environments. These sand bodies were formed within Upper Jurassic Heather and Draupne Formations. Both the formations were mainly shale dominated with comparatively high Organic content present in the Draupne Formation. The study area acquired markable sand deposist in 3 places (Figure 6.5, 6.6 and 6.7). These sand bodies contained mainly four different packages of sand bodies.

Near to well 9/24-b4 the sand size of the sediments was much coarser than elsewhere and the thicknesses of the sediment packages were also high. These sands are generally clean and occasional mud layer presences in these signify the flooding surface development.

In wells 15/3-3, 15/3-7 and 15/3-1S, the sand bodies of the different sediments packages were terminated simultaneously towards the north and the east. This established idea that the sediments mainly came from the East Shetland platform area. The sand bodies also contained conglomerates in a few places deposited by the high energy debris flows.

Facies development of the study area on the basis of the core information also reveals that the sediment deposition was mainly the results of deep marine debris and low density turbidity flows.

This deep marine sand bearing fan was developed in the hanging wall of the rift affected fault blocks whereas the shoreface deposits were developed in the footwall part of the half graben areas**.** Shore face deposits are marked by their common sedimentological structure like planer cross bed, trough cross bed, bioturbation, presence of coal flakes etc.

7.6 Reservoir Implication

It is already mentioned that the Upper Jurassic Heather and Draupne Formation are basically shale prone and that they are also good source rocks because of their high organic content.

The sand bodies are developed within the shale layers. The shale layer also works as a seal for the sand bodies carrying hydrocarbon. The sand bodies found in the study area have a potential to be a good reservoir for further exploration as the deep marine turbidite and debris flow deposits acquired hydrocarbon in wells 15/3-3, 15/3-7, 15/3-1S and 9/24-b4 in the study area. As regards the shoreface sand, wells 16/1-5 and 16/1-2 have showed the presence of hydrocarbon but the reservoir quality is not good.

The depositional model shows the spatial distribution of the Upper Jurassic sand bodies and the facies distribution from well to well. The vertical facies thickness maps of the sand bodies in the studied area finally portray the drainage pattern of the reservoir and help to place new well positions to get maximum recovery of hydrocarbon with minimum risk.

According to Underhill (1998) the sediments in the block 15/3 were sourced from the East Shetland Platform and Utsira high. But this study shows that the sediments in block 15/3 were sourced from the East Shetland platform during Late Jurassic time. This study shows no clear evidence of the sediments coming from the Utsira high during Late

Jurassic time as most of the seismic resolutions on the eastern margin of the study area were poor.

7.7 Projected Sedimentological Model

The final overall sedimentological model is summarized in Figure 7.3 which shows the distribution of facies associations within a structurally complex half graben basin and terrace area. It is assumed that the Upper Jurassic sub basins were deep water tubidite deposits and that the terrace was shoreface sand dominated deposits. The setting is one of regional transgressions with the sediment source or input point being controlled by the morphology of the basin (Howell, Flint and Hunt, 1996).

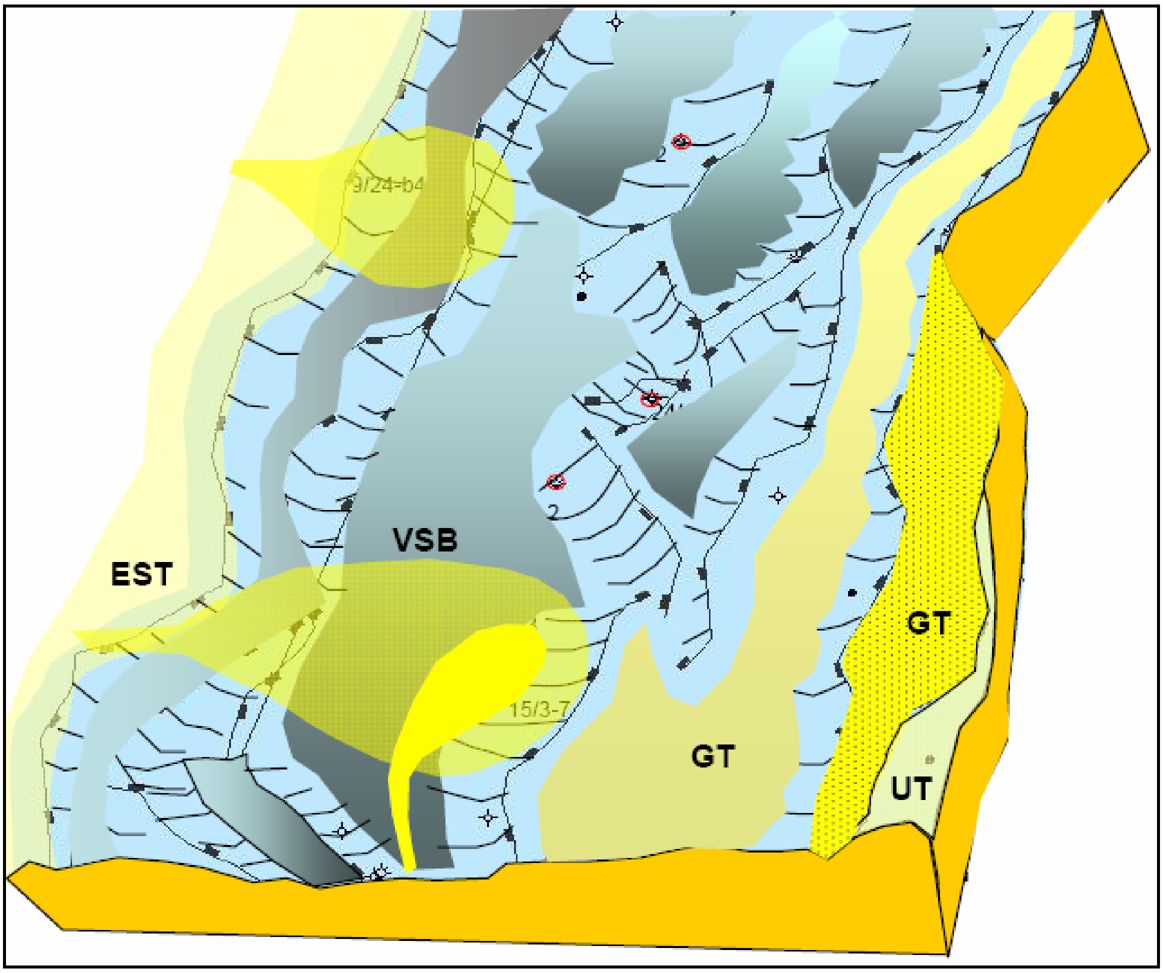

Figure 7.3 Conceptual depositional model, Upper Jurassic sand unit equivalent; UT- Utsira High, GT- Gudrun Terrace, VSB- Vilje-Vana sub-basin, EST- East Shetland Platform. Suggested depositional environment on Gudrun Terrace was Shoreface and VSB mainly deep water tubidite sand bodies deposits.

The discussion of a longitudinal versus a transverse orientation of individual turbidite complexes is fundamental to both an exploration and exploitation perspective. This is caused by the fact that depositional models form the basis for predicting sandstone thickness and quality and thereby guide the placement of innovative exploration. However, the depositional model needs to be remodelled and restructured on the basis of fresh data and information available from time to time.

In this study, the Upper Jurassic sand units are penetrated extensively by wells in the Gudrun area. Hence, little is known about the units in the structurally low and uplifted areas, and there remains some uncertainty about the precise orientation of the shoreface. Other factors that most likely had an influence on deposition of the sand units were the later inversions (Figure 4.4, near well 15/3-1S) tectonics in some areas. The relatively uniform pattern of the sequences in the wells studied here indicates limited effects of syn-sedimentary tectonism.

8 Summary and Conclusions

- During the late Jurassic rifting in the south Viking graben area in the North Sea formed thirteen maximum flooding surfaces which developed thirteen genetic stratigraphic sequences in the shale dominated Heather and Draupne Formations.

- Identified genetic stratigraphic sequences contain thick sand bodies mainly found in the western, south central and also in the eastern part of the study area.

- The sequences J63, J64 and J66A in the western part of the study area brought markable sands by high energy debris and turbidity flow deposits. In the south central part of the study area, thick sand bodies developed within the J63, J64, J66A and J66B sequences also developed by deep marine turbidite and debris flow deposits. The sand rich sequences thicken towards the west and pinch out towards the east and northeast of the study area. This may possibly signify that sediments were sourced from the East Shetland platform area.

- In the eastern part of the area, the sediments are poorly sorted and sands were developed in the shore face environment.

- The Late Jurassic (Oxfordian to Late Ryazanian) deep-marine to shoreface deposits formed a widespread sandstones unit of varying thicknesses and reservoir qualities in the Gudrun area. This area covered by 3-D seismic data and a reasonable number of wells, is hence well suited for studying sandstones geometries in complex settings and the architecture and heterogeneities of sand bodies that have implications for future exploration.

- Correlation and mapping of the maximum flooding surfaces show that they are mainly sigmoidal-shaped wedges with distorted thickness distributions in a depositional-dip direction. This is explained by changes in the rate of accommodation space versus sediment supply through time. During transgression the focus of sedimentation moved landward because of added accommodation in that region.

- The inherited topography controled the orientation of the Upper Jurassic successions. The turbidite complexes contained sediments mainly transported from west to east and occasionally from south to north through a narrow conduit, involving significant axial transport. The identification of whether these turbidite complexes are transversely or longitudinally oriented is very important for a valid prediction of reservoir thickness and quality, sediment pinch-out styles, and reservoir connectivity.

- The assimilation of these results has established a new depositional model within a sequence-stratigraphic framework that serves as input to reservoir models to help amplify recovery and identify new exploration targets.

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